Network Growth and Consolidation: The Effects of Cohesion and Diversity on the Biotechnology Industry Network

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Abstract:

The growth regimes of complex networks account for many of their structural features and practical effects. Social and economic networks, however, tend to expand along different pathways than their technological or biological counterparts. Complex inter-organizational topologies, we contend, are characterized by tight-knit clusters of prominent nodes whose dense connections to each other forge them into an elite that can play gatekeeper and arbiter roles in an expanding network. The characteristics of such emergent elites, however, depend intimately upon the structural locations of parties to new ties. Systems where cores deepen their internal connections conserve their position but may calcify. Those that expand their reach by forming connections to newcomers and to the network's periphery increase responsiveness at the possible cost of incoherence. We draw on twelve years of dynamic network data from the international biotechnology industry to demonstrate that a mix of expansive and conserving ties account for that industry's particular mix of stability and responsiveness. This structural view of network growth offers new insights into the distinctive features of social and economic networks, while linking models of network dynamics to established theoretical concerns in economic sociology, organizational theory, and innovation studies.

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Introduction.

The growth regimes of complex networks account for many of their macro features and functional characteristics (Newman 2003). For example, adding a small number of random links to a lattice with a fixed number of participants fundamentally alters path lengths and local clustering, thus shaping diffusion patterns (Watts and Strogatz 1998). Degree-biased attachments, which structure networks by directing new ties to partners already rich in connections, yield characteristic degree distributions centered on well-connected 'hubs' (Barabasi and Albert 1999). Such highly connected nodes render the topologies they dominate robust in the face of random error, but also highly susceptible to deliberate attack (Albert et al. 2000). Mixed logics of partner selection generate hybrid distributions but can result in emergent, durable macro-structures that shape the development of a field by constraining future attachments (Bearman et al. 2004; White et al. 2004). Even fleeting social interactions, such as conversations can generate structures that constrain participant behavior (Gibson 2003).

Mixed regimes and emergent structures are particularly characteristic of social and economic networks, which differ from physical and biological topologies – such as metabolic networks or the world wide web – in that they tend to be assortative (Newman and Park 2003). Put differently, social and economic networks generate prominent hubs as they grow *and* connect to one another, but the hubs vary internally and through time with respect to how they connect to one another. When the most prominent participants in a network establish linkages among themselves, the resulting 'core' group, i.e., interconnected clusters of central nodes whose linkages to each other reinforce their dominant positions, can dictate the developmental pattern of an overall network. Such an elite group of multi-connected organizations (Moody and White 2003) can act simultaneously as gatekeepers, because newcomers are biased to connect to one of the central incumbents, and as arbiters, who shape the overall direction and behavior of a field. In social and economic networks, such structurally defined 'classes' of nodes are particularly important for understanding both the trajectory of a field and the practical force that networks exert on operations and behavior.

We contend that the growth regimes of complex social and economic networks should be understood in terms of the role played by emergent, structurally defined classes of nodes. The structure of such systems and their effects on participants depend intimately upon the characteristics of gatekeepers and arbiters. Differences in the systematic patterns of connection linking the most prominent actors in a system to one another and to less well-connected alters have strong, predictable implications. Two stylized patterns capture features of networks dominated by assortative mixing and degree-biased attachment.

If central incumbents turn their finite capacities for linkages to connections with other central actors, the core participants in an expanding network will turn inward, and new ties will serve primarily to consolidate the position of prominent nodes. Network growth will thus consolidate an elite. Put differently, a strong tendency toward assortative mixing will generate a relatively impermeable, interconnected cluster of nodes whose stability comes at the price of insularity. Social and economic systems dominated by an inward-looking core, then, may opt for stability over responsiveness, and cement a stratification order that limits the mobility of newcomers and conserves the power of incumbents.

Alternatively, prominent participants may look outward by connecting to newcomers and less-well connected members who seek the resources and legitimacy that accrue from linkages to central partners. A network growth regime dominated solely by new ties that reach out from the system's core, however, may never cohere. Rather than ossifying, expansive systems can promote responsiveness and mobility. This very flexibility, though, may limit the network's resilience in the face of abrupt change or attack, and the resulting lack of coherence robs the core of influence. Stated in organizational terms, networks that grow by consolidating position are a recipe for oligarchy, while networks that grow through expansive connections are more characteristic of freewheeling market systems.

Actual social and economic systems manifest a mix of consolidating and expansive growth regimes, exhibiting varied levels of responsiveness, stability, and mobility. Some cohesive structure (Moody and White 2003; Newman and Girvan 2004) is necessary for network position to have real effects, while some openness is required if networks are to be adaptable. In short, understanding the emergence and effects of complex social and economic topologies requires that we consider tie formation in terms of expansion and consolidation at the system's core. We turn to a careful analysis of such a system, the biotechnology industry network, to assess the shifting mix of expansive and conserving ties that drive the network's growth and account for its efficacy.

The Contemporary Life Sciences.

The commercial field of the life sciences is deeply dependent on dense inter-organizational networks. Far-flung formal connections among diverse organizations comprise the industry's skeleton as well as its locus of innovation (Powell et al. 1996; Powell et al. 2004). This network is not stable, however; it grows markedly through the addition of both ties and participants. We analyze patterns in the formation of ties between biotechnology firms and different partner organizations to highlight a key, and too little discussed, characteristic of expansion in social and economic networks: the development and maintenance of a stable, structurally defined, elite whose members garner significant returns to their position while setting the pace for the entire field.

Describing tie-formation in structural, rather than dyadic or distributional terms, advances both our theoretical understanding of network dynamics and offers insights into biotechnology's peculiar mix of stability, responsiveness, stratification, and openness. Biotechnology firms, like those in other high technology fields, depend for success upon rapid and continuous innovation. In this industry, where scientific know-how is widely dispersed and the research frontier moves rapidly, no single organization can maintain all necessary capacities in-house (Gambardella 1995; Powell and Brantley 1992). Instead, science-based firms turn to collaboration with varied partners as a means to access to cutting-edge information, techniques, and resources. The resulting network grows as newcomers seek the legitimacy and resources offered by connections to established partners and as successful incumbents prospect for information that will aid them in winner-take-most innovation races. No wonder, then, that the industry network grows at a fairly stable rate.

The commercial life sciences emerged from university laboratories in the 1970s and continue today to rely on science conducted in academic and other public research organizations. As the field developed through the 1980s, hundreds of small science-based companies were founded. These start-ups were often funded by early stage venture capital firms. Later, multinational pharmaceutical concerns entered the game as the commercial benefits of new, targeted methods of drug discovery became apparent (Henderson and Cockburn 1996; Malerba and Orsenigo 1999). Making the leap from lab bench to market often required the regulatory know-how and distributional capabilities of multinational pharmaceutical firms. By the 1990s, though, the industry had come of age with the release of dozens of successful therapeutics, and many start-up companies became successful at drug development and distribution.

We analyze the growth of the industry network in this time period, when the industry becomes established and reliance on relational contracting with external parties becomes institutionalized (Powell et. al. 2005). Despite this first rush of stability, biotechnology's scientific base continues to evolve, forcing even the most established and successful firms to seek new discoveries and to develop novel competencies in order to maintain their record of success. Accomplishment in biotechnology depends heavily on research prowess (Powell et al. 1999).

Figure 1 tracks yearly trends in the number of ties and nodes involved in biotechnology, and provides an indication of the relative importance of organizational entrants and new connections. The cumulative pattern of growth is notable, representing a nearly 3 fold increase in formal alliances and just less than a 250% growth rate in organizational participants over a twelve year period.[1] This dramatic growth masks a fairly stable pattern of entry and tie formation, however. In every year save one (1999), more than 20% of observed ties were newly initiated. Similarly, each year witnessed entry by new

[1] These data are coded yearly for the period 1988-1999 from the April edition of *Bioscan*, an industry directory that tracks strategic alliances and organizational outcomes in biotechnology. Ties are reported yearly and represent formal contractual arrangements for R&D, licensing, commercialization, and finance. Nodes are organizations and include dedicated biotechnology firms (DBFs), venture capital firms (VCs), multinational pharmaceutical companies, government agencies, and public research organizations (PROs) such as universities, research institutes, and hospitals.

organizations, ranging between 8 (1999) and 22% percent of the network. The network's cumulative expansion, then, is driven by a relatively consistent pattern of annual growth.

As the network evolves, however, the ratio of ties (e edges) to nodes (n) is fairly constant, with an average e/n of 2.259 and standard deviation of 0.183. The broken line in Figure 1 gives a baseline for comparing changes in e relative to n by plotting the average (e/n) times n for each time period. This relative indication of density demonstrates the network's stable growth rate while highlighting the comparative stability of the e/n ratio, which tends to increase slightly from 1992 with an added uptick in 1998. An e/n ratio of two implies an average of one independent cycle per node, and a ratio of 2.3 implies 1.3 independent cycles per node, where each independent cycle adds to the structural cohesion of the network.[2] Thus, even while the network is growing, the *cohesive potential* of the network is conserved, neither diminishing nor rising, except for the rise in 1998.

[Figure 1 Here]

The pattern of rapid network growth and preferential attachment to key incumbents generates a network core comprised of a relatively small set of organizations. In addition to being key participants, as defined by network centrality, the core is also characterized by its cohesiveness, a robust pattern of independent pathways that connect each member to the others (Moody and White 2003; White and Harary 2001). Where the bulk of organizational participants can be separated from the biotechnology network by the simple expedient of severing one (or at most two) ties, organizations at the field's core are connected to each other by between four to six node-independent pathways. In other words, the elite that emerged as this industry grew is both highly robust (separating an organization from the group requires that at least four ties be broken or four connecting nodes removed) and difficult to enter (a challenge that requires newcomers to forge ties to multiple well-connected alters).

[2] A set of cycles is considered *independent* if each cycle in the set has at least one edge that is not found in any other cycle in the set.

Over time, the core's relative size remains constant, hovering at or around 10% of the organizations active in the network. But the level of cohesion that defines this structural elite increases; in 1988, 66 organizations represent a 4-core whose coherence depends on the four node-independent pathways connecting its members. By 1998, 102 organizations occupy a six core. While the size of the core remains comparable, the bar for entry is raised. This pattern is precisely what one might expect from a simple model of growth that matches degree-biased (hub-creating) tie formation with assortative (hub-connecting) mixing patterns. These graph-theoretic concepts are well suited to explaining the emergence and maintenance of an exclusive, stable network elite. The logic underpinning that explanation also suggests that network growth (particularly in situations where individual nodes can accommodate only a finite number of partners) will inexorably drive emergent elites to turn inward to restrict access and possibly form an oligarchy. But such a move towards closure is a recipe for ossification and stagnation, a fatal step in high-velocity, science-driven fields.

The biotechnology field, however, has seen the development not of an oligarchy, but of an 'open' elite whose dominant activities and characteristic members shift over time as incumbent organizations prospect for new resources, information, and partners. The center of this industry is characterized by stability, but not stasis. The apparent adaptability of the core raises important questions for growth-based theories of network dynamics. These questions parallel a central, and long-standing question, in innovation and organizational studies concerning the appropriate balancing of exploration and exploitation (March, 1991).

Network Growth - - Consolidation and Expansion.

We draw on descriptive analyses of key points in the evolution of biotechnology to make progress toward answering a deceptively simple question: "What mechanisms of network growth allow a system to simultaneously expand and consolidate?" We first analyze the industry's trajectory in structural terms, then present detailed analyses of a natural experiment that saw a cohesive core disentangle and the subsequent successful consolidation of an even larger elite. Examining the correlates of both consolidation and decay provide insight into network dynamics, and explain how one particular expanding network has proven resilient against lock-in.

Biotechnology networks grow as organizations search for novelty and access information and resources through their connections, a process driven by exploration and a search for diversity, rather than pure degree bias (Powell et. al. 2005). The mixed attachment patterns that are dominant in this field helped forge a cohesive network core whose dense and redundant pattern of inter-connection generates stability, while speeding the flow of information and resources among its members. Cohesion, though, raises the possibility that the field's most prominent players will, by virtue of their repeated ties, develop comparable skills and competencies over time. Such homogeneity could limit the capacity of organizations to adapt to changing scientific, institutional, or economic conditions. In short, the development of a highly cohesive elite could lead to calcification, as an increasingly intertwined group becomes more similar in outlook and competencies.

This danger may be particularly severe in biotechnology, where high-velocity scientific developments occur in the context of expensive innovation races, costly long-term regulatory processes, and fixed term intellectual property rights. These conditions ensure that the returns to success will be large, but time limited in a regime that can punish even the most accomplished firms for resting on their laurels. Both the institutional and structural features of the industry, then, seem tailor-made for innovation to usher in the winds of creative destruction (Schumpeter, 1938).

If this Schumpeterian pattern holds, then we would expect industry elites to fall victim to periodic shake-outs as generations of organizations that entered the core on the wings of once novel scientific developments become less innovative as they turn inward to consolidate their positions. In a world governed by such processes, networks would grow primarily as ties form among elites and among newcomers working on the scientific frontier. Both groups would consolidate their positions, but eventually a successful, inter-connected group of entrants would supplant the existing core at the center of the network, setting the stage for recombination and renewal.

Consolidation, homogeneity and creative destruction should result in cyclical patterns of growth with few new ties forged from the center to the edge of the network. Newcomers should enter the core en-masse, supplanting their predecessors rather than benefiting from sponsored mobility, thus few elite organizations would remain at the center of this fast-paced industry for long. But such a competitive, entrant-driven process of selection has not yet been observed; instead the small cohesive core at the center of the network has been highly active in the formation of new ties. Moreover, the connections by the core both span the network and deepen connections.

Figure 2 presents data on the most cohesive cores of the biotechnology industry network by year. We define that core as the set of organizations connected by the largest number of node-independent pathways in a given year (White & Harary 2001). The more pathways that connect a group of organizations, the higher their cohesion level. The most cohesive cores for years 1988-1999 are 4-, 5- and 6 cores, and their evolution in percentage of organizations in the top core is shown by the solid line in the figure. The upper line graph shows the proportion of new ties involved in the top core. The broken lines in the lower graph show the steady growth in percentage of organizations in the 4-cohesive core, which tracks the lower broken line in Figure 1, and also the steady growth in the 5-cohesive core once it emerges as a conserved feature of the network in 1995.

[Figure 2 Here]

Note in figure 2 that that a very small percentage of organizations are involved in a large proportion of the new ties. Indeed, the members of the highest core in any one year account for between 28 and 70% of the new ties formed in the following year. The size of the highest core in the network remains relatively constant for more than a decade; however, cohesiveness increases without curbing new tie formation by members of the core. The biotechnology network appears to follow neither a pure logic of degree-biased and assortative growth, nor a Schumpeterian process of lock-in and creative destruction. Instead, the core of the network displays both expansive and consolidating tendencies.

In order to investigate the mechanisms by which network growth proceeds, we analyze two key points in the industry's evolution. The 1992 to 1993 transition witnessed the unraveling of a cohesive core as a small (35 organizations) five core failed to maintain its level of internal coherence and disconnected into a four core. Similarly, the 1997-1998 transition captures the successful consolidation of a six core from the prior year's five core. The analyses highlight an important conceptual distinction between 'conserving' ties -- which deepen linkages among members of the core and contribute to consolidation at the level of the network, and 'expansive' connections – which link organizations at the center of the network to other participants, contributing to the network's adaptability in the face of a changing competitive and scientific environment.

Transformations at the core of the biotechnology network.

We employ a series of network visualizations[3] to illustrate a structural view of network growth and to examine instances of consolidation and disentangling by the core. Our data for these analyses are formal contractual alliances among biotechnology firms and between those firms and a diverse set of partners. Our tie data encompass some 8,818 ties linking nearly 3,000 organizations over twelve years from 1988-1999. We distinguish among four activities: (1) Science ties entailing either collaborative R&D or funding of basic research; (2) Finance ties that represent both minority and majority equity investments; (3) Commercialization ties involving downstream development, including either clinical trials, manufacturing, marketing, or distribution agreements; and (4) Licensing ties that transfer the rights to patents or other forms of intellectual property. These ties link six distinct types of organizations. Our focal organizations are 482 dedicated biotechnology firms (DBFs), that focus on human therapeutic and diagnostic drug development. Their partners include biomedical supply firms, public research organizations (PROs) such as universities and nonprofit research agencies, government agencies such as the National Institutes of Health, venture Capital firms (VCs), multinational pharmaceutical and healthcare firms (Pharma), and other DBFs.

[3] All network images were created using Pajek and are based upon a pair of one minute minimum-energy network optimizations from random starts (Fruchterman and Reingold, 1991; Kamada and Kawai 1989)

We first focus on two key transitions in the growth of the network. Next, we analyze the mix of expansive and conserving ties forged by members of the network core at two time periods. Finally, we examine the composition of activities and organizations that comprise the stable and unstable cores.

Figures 3 and 4 represent two slices of network growth. The former traces the transition from 1992 – a year dominated by a small (35 organization), highly cohesive five core – to 1993 – which was dominated by a much larger (161 organization), less cohesive four core – in order to examine the processes of tie formation that lead a tight cohesive cluster to unravel. Figure 4, in contrast, tracks the transition from 1997 – the last in a series of years dominated by a stable five core – to 1998 – the first year to see the formation of a six core. This example of consolidation witnessed a shift toward greater cohesion as the 168 organizations that occupied the 1997 five core were whittled down to a 102 member six core.

In both figures, we begin with an image of the starting point - - the main component of the full network in the first year. The main component is the largest cluster of weakly connected organizations. We then present a main component image of ties initiated the following year, before dividing those new ties into three structural categories. Peripheral (blue) ties are new connections that do not involve a member of the prior year's core. Expansive (green) ties reach out from the core, linking one member of the most cohesive cluster to an outside organization. Finally conserving ties (red) form a dyad where both partners members of the prior year's core. Reading the figures from left to right offers a flipbook view of network growth. In both images, node size represents standardized degree centrality, node color reflects the highest cohesive core to which an organization belongs, and shape (in the new tie images) distinguishes between new organizational entrants (triangles) and incumbents (circles).

Consider Figure 3, when a core failed to maintain its coherence and unraveled. Note first the relatively small number of red (core) nodes in the image of the 1992 main component. This 1992 five core is the smallest core we observe in the dataset. Nonetheless, the members are both relatively tightly clustered at the center of the network, and dispersed in the next image that represents the main component formed by the 643 ties initiated in 1993. This dispersal suggests that core organizations are used new ties to search for novel partners and competencies (Powell et. al. 2005; White et. al. 2004). The prevalence of green and blue nodes in the new tie network points to the predominance of both expansive and peripheral connections, however. This implication is borne out in the next three images. Blue, peripheral ties are far and away the most important category, accounting for more than 75% of newly initiated connections. Green, expansive ties account for another 23% of network growth, while red, conserving linkages amount to less than 2%. The sizeable minority of expansive ties clearly emphasizes the importance of the core, but the near absence of ties among those organizations accounts for its loss of coherence, which is apparent in the large and fairly dispersed group of red nodes at the center of Figure 3's final image.

Figure 3 portrays network growth that is dominated by peripheral and expansive connections, suggesting two possible explanations for the 1992 core's subsequent undoing. This small cluster of organizations may have been too small to sustain a critical mass of conservative connections. Alternatively, the organizational competencies and mix of activities that constituted the core may have been insufficient to provide guidance to the search for novelty. The core firms in 1992 reached out to distant parts of the network, an expansive move that connected with members of the periphery, but may not have generated productive synergies.

[Figure 3 Here]

Figure 4 illustrates a very different process, one that mixes conserving and expansive ties in the consolidation of an elite core whose reach extends across the entire network. Note first the number and dispersion of red (core) nodes in the 1997 five core. This year represents the end point of a three year period in which the five core expanded from 94 to 168 members. That expansion came in lieu of tight inter-connections among the core, as evidenced by the relative spread of these nodes across the middle of the network. The organizations that comprised the 1997 core were very active in forming new ties, and their broad reach across the main component formed by ties initiated in 1998 highlights the importance of exploration. The clearest distinction between the case of unraveling in Figure 3 and Figure 4's instance of consolidation is apparent in the blue, green, and red images that track peripheral, expansive, and conserving ties. Consider the peripheral image, which portrays ties that do not involve core organizations. While nearly 37% of ties initiated in 1998 were peripheral, the impact of that relatively large minority is mitigated by the dense pattern of expansive ties that reach across the network. This is confirmed by the empty center of the peripheral tie image.

The 1997 core remains active in seeking connections to new partners. Just less than 46% of new ties connect a core organization to a partner at a lower cohesion level. The center of gravity in the network has clearly shifted, with core organizations involved in 63% of new ties. There is still action at the margins as in 1993, but growth now depends on the center and the direction of that growth combines expansive and conserving connections. Note the tight cluster of red ties forged between members of the core. Over 17% of new ties are conserving in this year, a ten fold increase over the 1992-93 time period.

The consolidating and stabilizing effects of that increase are apparent in the final image of Figure 4, which shows a more cohesive and exclusive six core, tightly clustered at the center of the 1998 main component. The organizations that entered this new core were overwhelmingly those that forged both expansive and conserving connections. The logic of growth has shifted for the system, in a manner that simultaneously heightens the exclusivity and openness of the center.

[Figure 4 Here]

Viewing the network's growth through a structural lens offers new insights into the particular mix of features that characterizes biotech, and raises further questions about the etiology of cores and the processes underlying their formation, dissolution, and consolidation. Recall that the industry is both highly structured and widely diverse, with multiple types of participants pursuing a mix of activities that span time scales and the development process. In order to examine the joint implications of structured growth and institutional diversity, we turn to a set of images that recast these growing cores in terms of types of organizational forms and activities.

Figure 5 represents the expansive and conserving ties forged in 1993 and 1998, but now colors connections to represent activity types and nodes so that we can assess the mix of organizations. Node size again reflects the prior year's network degree. Note first the mix of large (high degree) and small (low degree) nodes active in the new tie networks. This diversity is suggestive of a mixed attachment logic. The variation in centrality among participants in the core suggests the need to distinguish between the quality and quantity of ties. A large number of ties to peripheral actors may generate benefits, but access to the network's core requires fewer high quality linkages. Those connections, however, must be forged with particular partners. In social and economic networks, exclusivity matters.

[Figure 5 here]

The mix of organizations in the core also matters. Consider the image in the upper right hand corner of Figure 5, which represents conserving ties among members of 1992's unstable five core. The paucity of conserving ties is the proximate cause of disintegration; but consider the relatively uniform colors of the nodes. With two notable exceptions - - the brown nodes that represent the National Institutes of Health and the National Cancer Institute, two government agencies that are of central importance to the development of both the industry and its science – all members of the core are commercial entities, membership is evenly split between DBFs and large, diversified pharmaceutical corporations. The ties that form among members of the core, connect only for-profit competitors, which is not only a challenging task but one that limits diversity.

Only two of the new ties formed among members of the core are research collaborations (red ties) and both link the same DBF to the NIH and the NCI. This firm, Oncogene Sciences, was founded in 1983 by scientists from the NCI and NIH and maintained tight connections with those agencies ten years later. The majority of new ties formed among members of the 1992 core link biotechnology firms to pharmaceutical companies in collaborations that focus on commercializing products, equity investments, or transfers of intellectual property. The new action apparent in this year is overwhelmingly oriented toward exploiting existing research and development, rather than generating novel innovations.

The expansive ties formed in 1993 manifest a much different pattern. Almost 42% of those ties are scientific collaborations, while nearly 45% emphasize commercialization and licensing arrangements. Expansive ties formed in 1993 mix both early stage research collaborations and later-stage development efforts, insuring a mix of exploratory and exploitative activity for firms in the core. The parties to these ties are also more diverse than the membership of the core. Government agencies remain central ; indeed, the NIH and NCI account for more than a quarter of the expansive ties formed. Even in the early 1990s, the public science roots of biotechnology are apparent, and federal funding agencies play a key role in ushering promising newcomers into the center of the network.

Expansive ties also bring a new portfolio of old and young biotechnology firms, venture capital firms, and public research organizations - - such as universities - - into the mix. The overall message of the representations in the top half of Figure 5 is that the core lacked sufficient heterogeneity and thus had to search outside for novelty. Moreover, the composition of the core was overwhelmingly for-profit firms. In an industry that has seen waves of mergers and consolidations among its largest numbers, linkages may have been previews to merger rather than opportunities for exchanging complementary skills.

Organizational diversity, a combination of both upstream and downstream activities, and a critical mass of conserving connections are all absent in the 1992-1993 transition. The successful consolidation of the 1998 six core tells a diametrically opposed story. The continuing importance of key government agencies is the only constant. The ten-fold increase in conserving ties across these two time periods is accompanied by a qualitative shift in the character of connections initiated by members of the core. Indeed, the conserving ties formed in 1998 bear a striking resemblance to the expansive ties that contributed to the unraveling of the 1992 core. Fully 41% of the ties that deepened connections at the core of the 1998 network are R&D collaborations. Another 40% are downstream commercialization and licensing connections. Finance ties too play an important role, but where money flowed from multinational pharmaceutical companies to biotechnology firms in 1993, new finance ties forged among core members in 1998 now represent investments from a multiplicity of sources, including established biotechs, venture financiers, and pharmaceutical companies.

By the end of the 1990s, membership in the core affords the prospect of multiple sources of financing, a healthy influx of novel information developed through collaborative R&D, and access to both development muscle and intellectual property developed by a variety of organizations. The very mix of partners and activities that led core organizations to favor expansive ties in 1993 are, by 1998, available in conserving connections. These connections can be forged with a greater sense of confidence as core organizations are now so multi-connected that news about potential partners can travel quickly and through numerous channels. Members of the 1997 five core are separated by an average of 2.6 network steps. The more exclusive six core that formed as a result of 1998's conserving ties is even more closely linked, with each node only 2.3 steps from all others.

The increasing diversity, range, and clout of the core by the end of the 1990s could be a recipe for oligarchy, but even as the core gains the ability to form deep internal connections, the members reach across the network and expand it. Consider the lower left hand image in Figure 5, which represents expansive ties formed in 1998 that account for the bulk of the network's growth. These ties also reflect a mix of activities, but the highest volume (36%) of expansive ties are financial. Both R&D collaborations and commercialization deals remain important, with each accounting for about a quarter of expansive ties. Even though members of the core could rely solely on each other for a range of activities and partners, they opt not to do so. The number and diversity of conserving ties helps to consolidate the core, but the expansive ties enhance search and provide novelty. In tandem, the combination of ties provides a balance between expansive and conservative modes of growth.

Table 1 summarizes the data on new tie formation in 1993 and 1998, presenting the proportion of new ties by type (peripheral, expansive, conserving), activity (science, finance, commerce, licensing), and dyad (organizational form of partners). The patterns are striking. Note the important shift in the valence of network growth, from dominance by peripheral ties in 1993 to a mix of conserving and expansive ties in 1998. Consider also the overall role that different activities play in the new tie network, where a series of shifts herald the transformation of pharmaceutical firms from commercialization partners to financiers and collaborators. The mix of dyads, too, is informative as it highlights the central role of non-proprietary partners such as government agencies and PROs. The central position and size of the brown node that represents the NIH evidences the industry's continued reliance on public support and public science. Finally, the growing importance of venture capital firms as a source of funding and as matchmakers between established companies and promising newcomers, heralds the rise of a new model of finance that emerged with biotechnology and other high-tech sectors (Gompers & Lerner, 1999).

[Table 1 Here]

New and continuing relationships within the core

A structural view of biotechnology's network growth offers key insights, but neglects one other conserving force. Ties in this industry can last for multiple years. New ties formed between members of the core deepen existing relationships that link participants at the center of the network, while ties that pull in new participants afford the possibility of exploration. We turn now to a close examination of the ties linking members of the 1992 five core and the 1998 six core. We continue to color ties to portray activities and nodes represent organizational form.

Figure 6 portrays the 'starting point' for the 1992- 93 transition, showing the ties connecting the 35 members of that year's five core. Those organizations are linked by 164 ties in 1992. Figure 6 also highlights the corporate dominance of 1992's core. All but two of the organizations represented here are biotechnology or pharmaceutical firms. The colors of ties point out the importance of financial, licensing and commercialization links in maintaining this core's coherence. The biotechnology firms that are members of this core are among the most notable of first-generation companies, including Genentech, Chiron, Biogen, and Centocor. The pharmaceutical firms represent the industry elite of the late 1980s, corporations that moved into biotechnology in a somewhat tentative way through multiple affiliations with DBFs.

This image also suggests the fragility of a core that is composed primarily of proprietary organizations. Where government agencies and public research organizations rarely go out of business or merge, firms in the fast-moving biopharmaceutical industry frequently merge and some fail. The decade of the 1990s was a period of extensive merger and acquisition activity among pharmaceuticals. Consider one merger that may have helped contribute to the instability of this core. Genetics Institute, a notable first-generation Boston area biotechnology firm, had nine ties to other members of the five core. Three connections link GI to other visible partners, such as Genentech and Chiron, while the remaining six connect the firm to pharmaceutical giants. These ties include an R&D connection forged between GI and American Home Products. In 1993 American Home Products acquired GI, and subsequently AHP was merged with Wyeth. ***(Get story correct, and dates. Looks like a complicated one. A quick look at http://informagen.com/Resource_Informagen/report.php?mrn=2752 and http://www.wyeth.com/about/period4.asp suggests that AHP bought 60% of GI in 1992 1993, depending on whether you count the option or the actual acquisition as the date. AHP acquired the rest of GI in 1996. AHP also acquired American Cyanamid in 1994 and through that acquisition came to hold a majority share of Immunex, another major DBF. I haven't been able to untangle the AHP Wyeth link. Some sources suggest a merger, some a name change, so we may want to be careful here)*** **[Woody, does this square with your sense of the story? If So, would you add a line or two?].**

[Figure 6 Here]

Figure 7 presents the newly consolidated 1998 six core, and offers a rather different image. The 102 organizations that emerged from 1997 five core are connected in 1998 by 719 ties. Almost 27% of those ties are new, but the bulk of this core's cohesion results from the continuation of relationships forged in prior years. This network is characterized by both density and diversity in organizational form. The increasing role of public research organizations -- note the orange nodes that represent the University of California, Stanford, MIT, and Memorial Sloan Kettering Hospital -- and the increased size and centrality of the NIH add a leavening of stability to the core that was absent in 1992. The appearance of gray nodes representing venture capital firms signals the increasing impact of specialized, early stage financiers, although their position at the edges of the image suggests their specialized role. The combination of VCs and PROs offers new routes to entry that are not reliant on other proprietary firms.

The types of ties that are predominant also suggest the growing diversity of the core. Research ties dominate the network and are most apparent in the 'waterfall' of red connections that link chains of biotechnology firms to one another and to the most central players in the core. That research corridor includes not only the NIH and NCI (brown nodes), but also Memorial Sloan Kettering and the University of California (orange nodes), a mix of both new and established biotechnology firms (Genzyme, Genentech, IDEC, Cubist) and several large pharmaceutical companies (notably Hoffman LaRoche and Bristol Myers Squibb). Where R&D in the 1992 core was conducted though ties to government agencies, the reach of science in the 1998 core is broader and the participants much more diverse. The continued success of this core will rest on continued exploratory innovation, organizational diversity and the resilience offered by a network that spans institutional arenas and selection environments, and by the increasing cohesiveness of the core itself.

Expansion, Consolidation and the Growth of the Biotechnology Industry

The biotechnology industry is an instructive case for theories of complex network dynamics. The industry grows at an impressive and stable rate through the formation of new ties and the addition of new nodes, following a mixed attachment regime that yields a topology centered on small number of densely interconnected nodes. The size of that core remains proportionally stable from year to year and the level of cohesion that defines it increases. But the trend toward an increasingly inward focused core carries few of the negative consequences that one might expect to accompany the formation of an oligarchy. Instead, an 'open' elite mixes conserving connections that deepen the core's capacity to innovate while expanding the mix of members and the range of activities. The balance between expansive and conserving ties and the resilience and stability offered by an organizationally diverse core contribute to the multivocality of central participants and the robustness of the overall field (Powell et al, 2005).

Understanding the growth dynamics of complex social and economic networks, then, requires attention not only to dyads and degree distributions, but also to the emergence and maintenance of structurally cohesive classes of organizations and the institutional variety reflected in these classes. When viewed though this structural lens, new ties represent three types of additions to a system, conserving, expansive, and peripheral. The pattern and distribution of these types of ties helps account for the functional characteristics of the system, variations in the size and importance of the core, and mobility patterns. Many of the pragmatic features that distinguish social and economic networks from their technological and biological counterparts are only apparent when their dynamics are viewed structurally. We contend that this approach represents fertile ground for the merger of organizational theory and economic sociology's concerns with the practical effects of network position on firm and industry performance, and complex network theory's concern with the topological and functional characteristics of networks defined by particular growth regimes.

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Figure 1. Network Growth, 1988-1999: Nodes and Ties

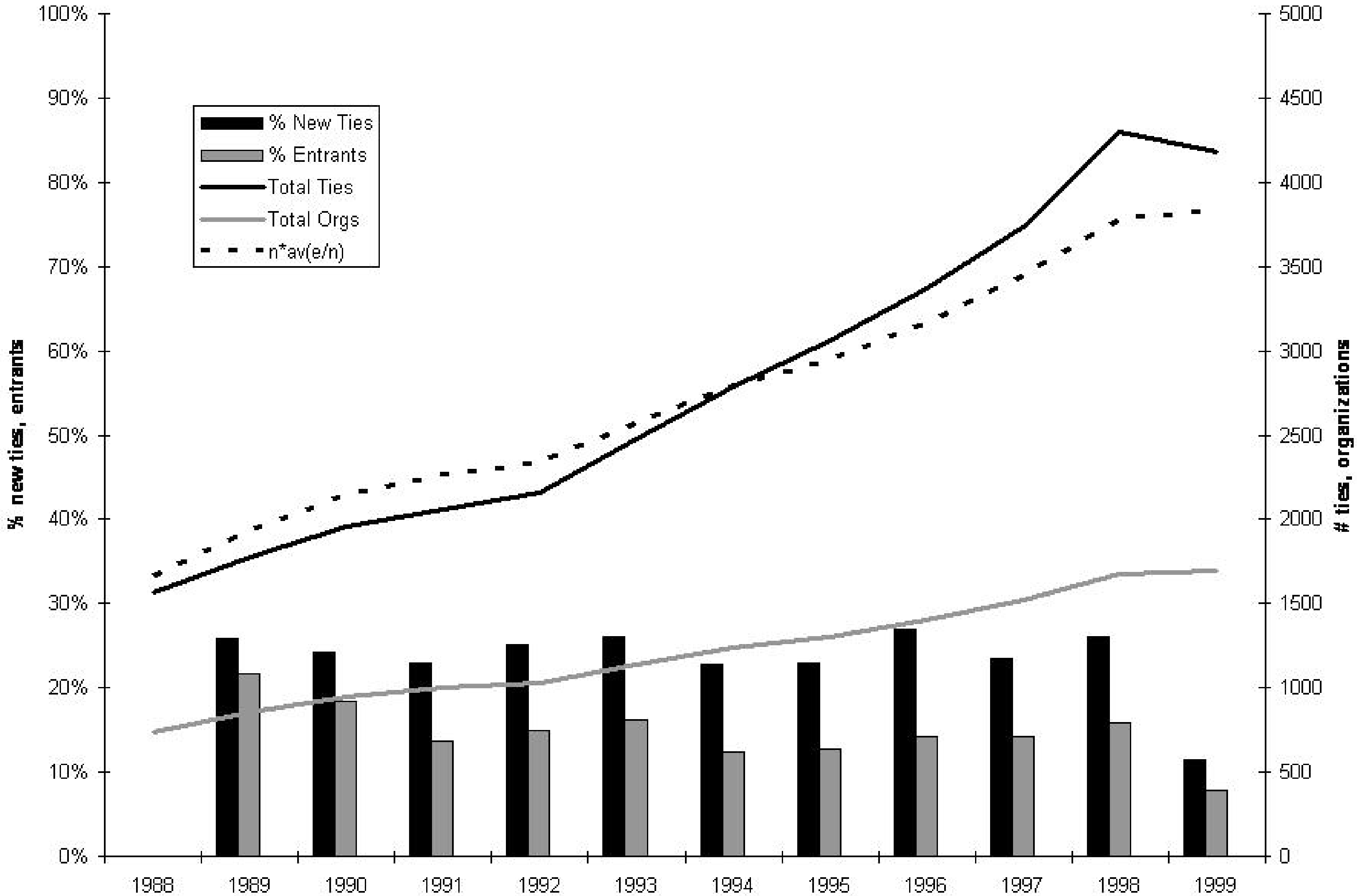


Figure 2. Network Growth, A Structural View

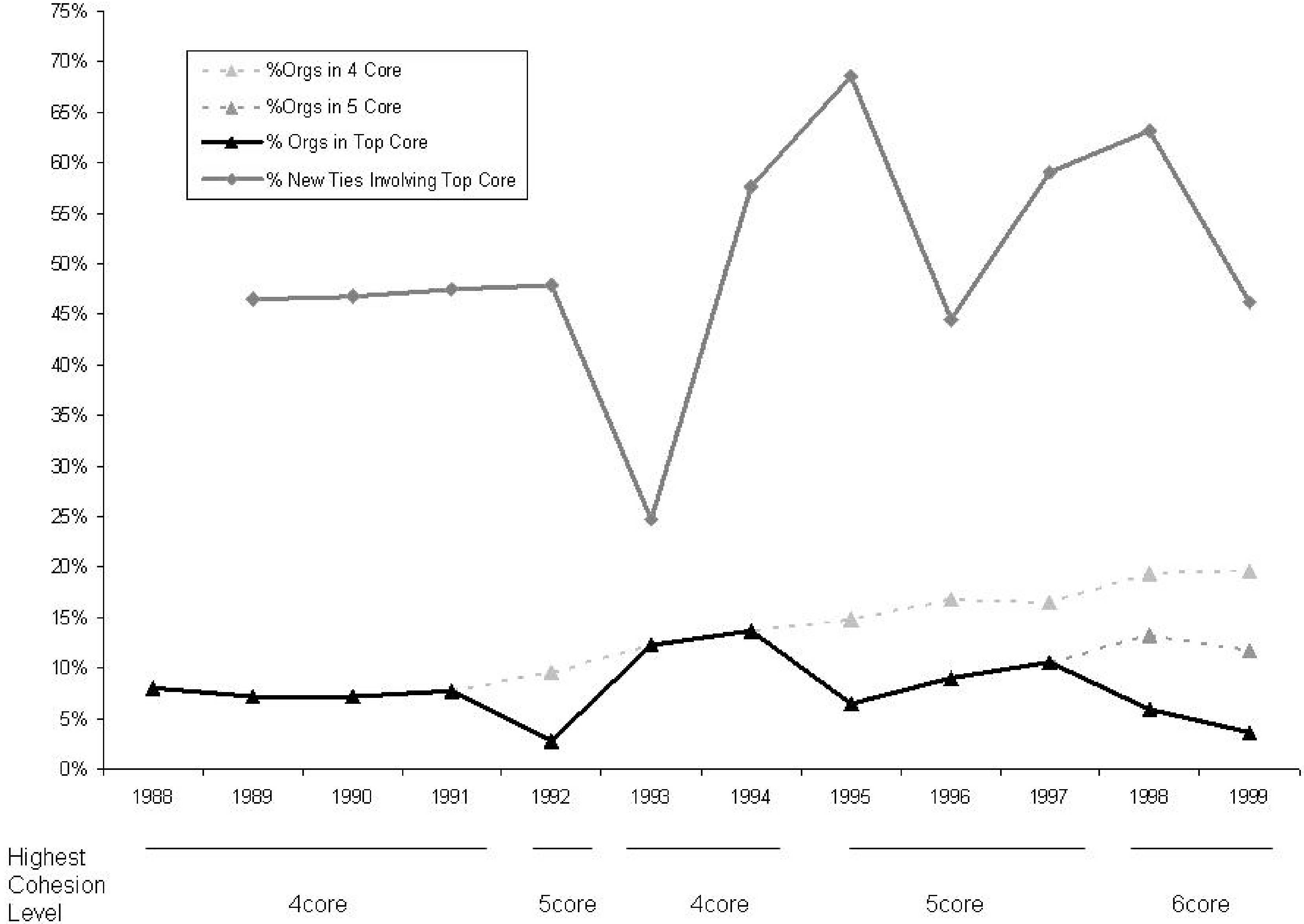
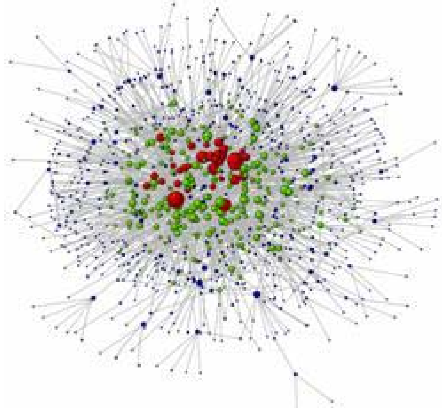
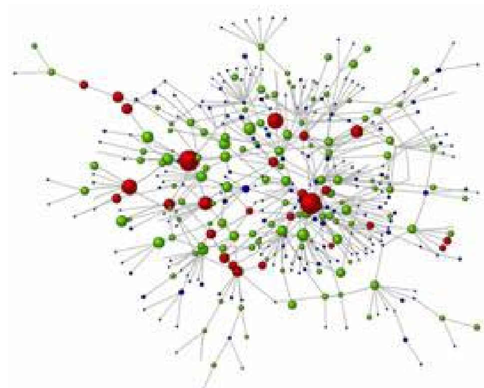


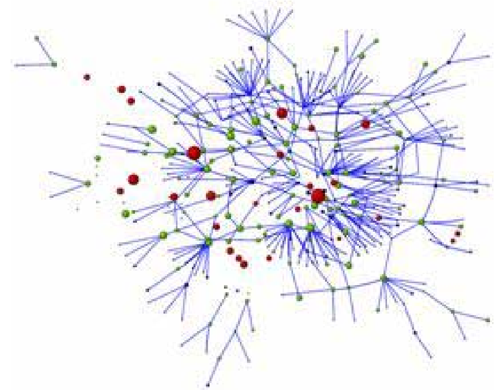
Figure 3. Network Growth: The Initial Core Unravels, 1992-1993



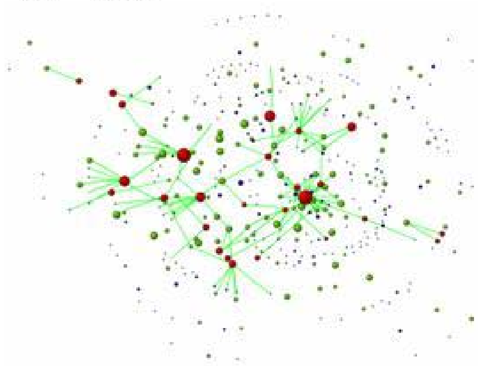
1992 Main Component,
Red = 5 core



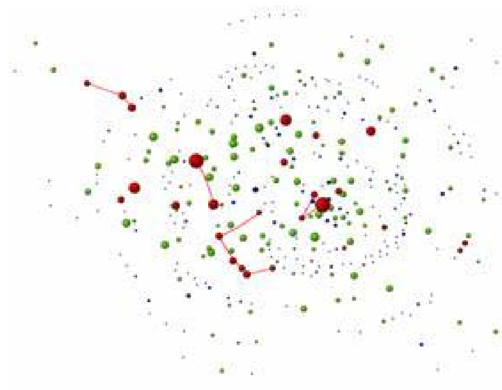
Ties Initiated in 1993



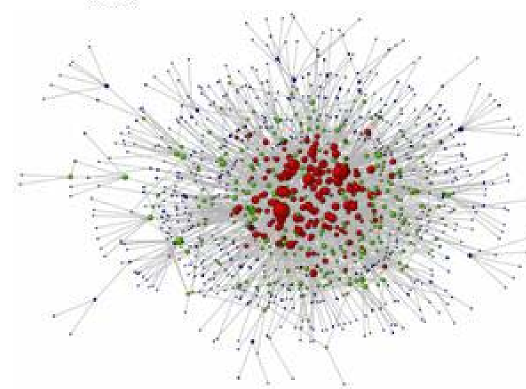
'Peripheral' ties that do not involve 1992 core



'Expansive' ties from core to non-core organizations



'Conserving' ties among core organizations



1993 main component, Red = 4 Core

Node Key

RED – Highest Core

GREEN – Middle Cores

BLUE – Lowest Cores & Entrants

Size = Degree (prior year in new tie images)

Triangle = New Entrant

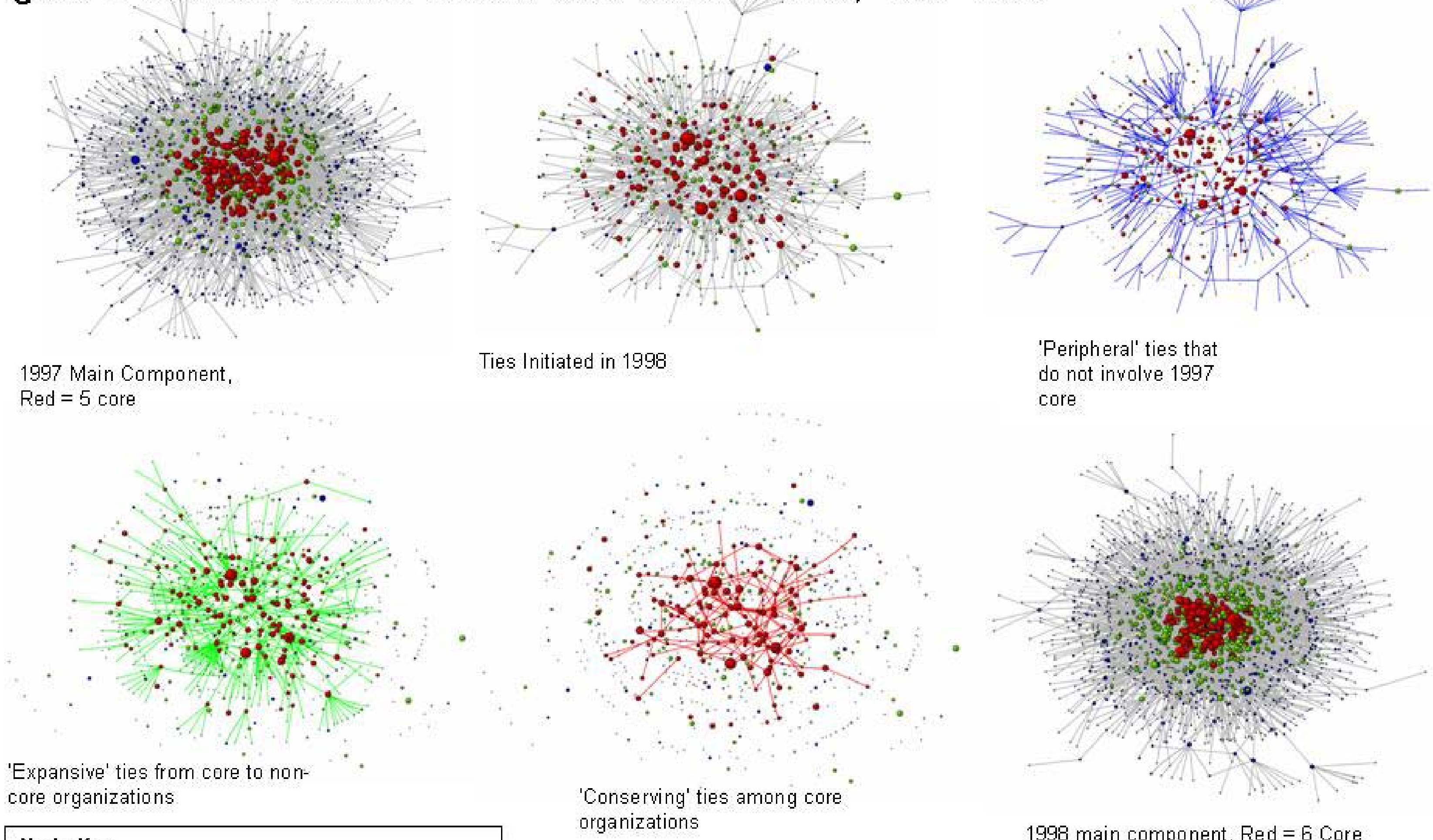
Tie Key

RED = Conserving Ties

GREEN = Expansive Ties

BLUE = Peripheral Ties

Figure 4. Network Growth: A New Core Consolidates, 1997-1998



Node Key

RED – Highest Core

GREEN – Middle Cores

BLUE – Lowest Cores & Entrants

Size = Degree (prior year in new tie images)

Triangle = New Entrant

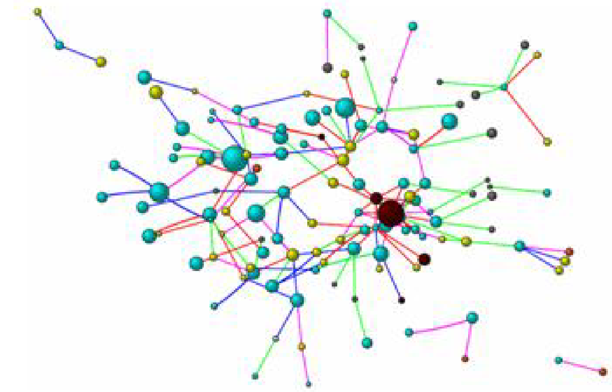
Tie Key

RED = Conserving Ties

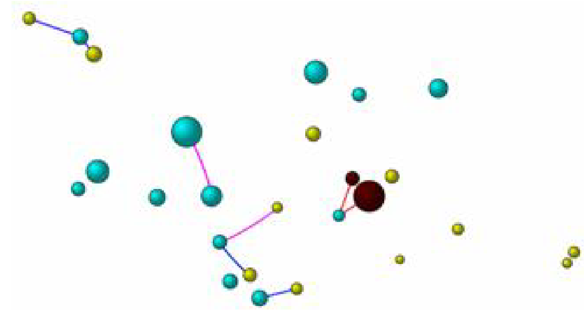
GREEN = Expansive Ties

BLUE = Peripheral Ties

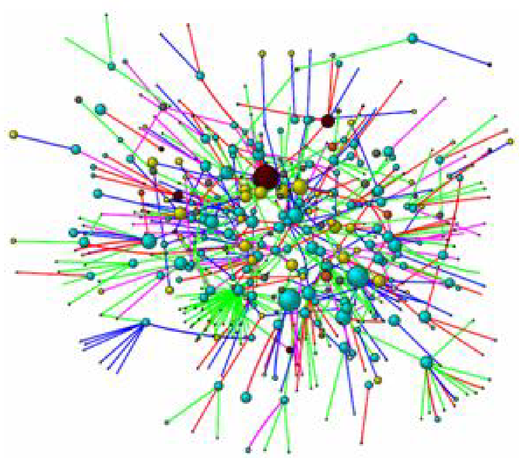
Figure 5. Expansion and Consolidation: New Ties 1993 and 1998



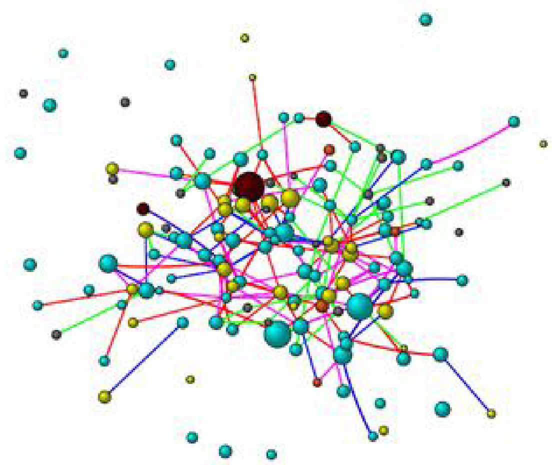
'Expansive' ties from core to non-core organizations, 1993



'Conserving' ties among members of the highest core, 1993



'Expansive' ties from core to non-core organizations, 1998



'Conserving' ties among members of the highest core, 1998

Tie Key
Red = Science
Green = Finance
Blue = Commerce
Magenta = Licensing

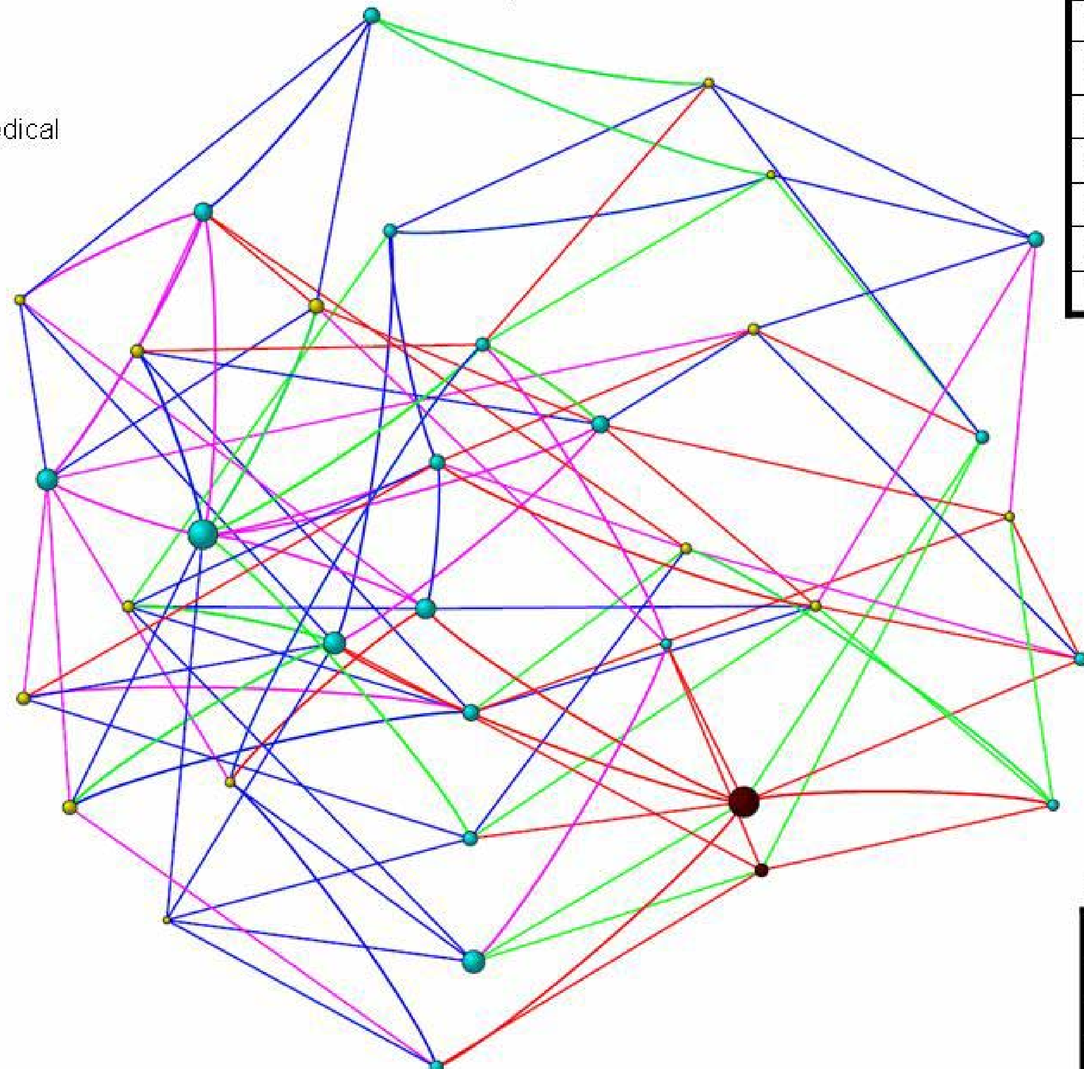
Node Key
Cyan = DBF
Silver = Other Biomedical
Orange = PRO
Brown = Gov't
Green = VC
Yellow = Pharma
Triangle = New Entrant
Size = Prior Year's Degree

Table1. New Ties by Type, Activity, and Dyad: 1993,1998

	1993			1998		
	Peripheral	Expansive	Conserving	Peripheral	Expansive	Conserving
Total	75.2%	23.0%	1.7%	36.8%	45.9%	17.1%
By Activity						
Science	18.0%	9.6%	0.3%	8.8%	11.4%	7.0%
Finance	30.3%	3.1%	0.6%	16.4%	16.7%	3.2%
Commerce	13.9%	4.9%	0.3%	6.4%	11.7%	3.3%
Licensing	13.0%	5.5%	0.5%	5.1%	6.1%	3.6%
By Dyad						
DBF-DBF	9.9%	5.6%	0.3%	3.4%	7.0%	4.6%
DBF-Other	8.2%	2.4%	0.0%	5.6%	7.4%	0.0%
DBF-PRO	12.2%	0.3%	0.0%	4.9%	2.3%	0.7%
DBF-Gov	3.9%	6.1%	0.3%	2.9%	3.3%	1.3%
DBF-VC	23.8%	0.5%	0.0%	14.0%	12.5%	2.1%
DBF-Pharma	17.2%	8.2%	1.1%	6.0%	13.4%	8.4%
Core Nodes, Prior Year		35			168	
Ties Initiated, Current Year		643			1121	

Figure 6. 1992 5-Core, New and Continuing Ties

Node Key
Cyan = DBF
Silver = Other Biomedical
Orange = PRO
Brown = Gov't
Green = VC
Yellow = Pharma
Size = 1992 Degree



Nodes

DBF	19
Other	0
PRO	0
Gov	2
VC	0
Pharma	14
Total	35

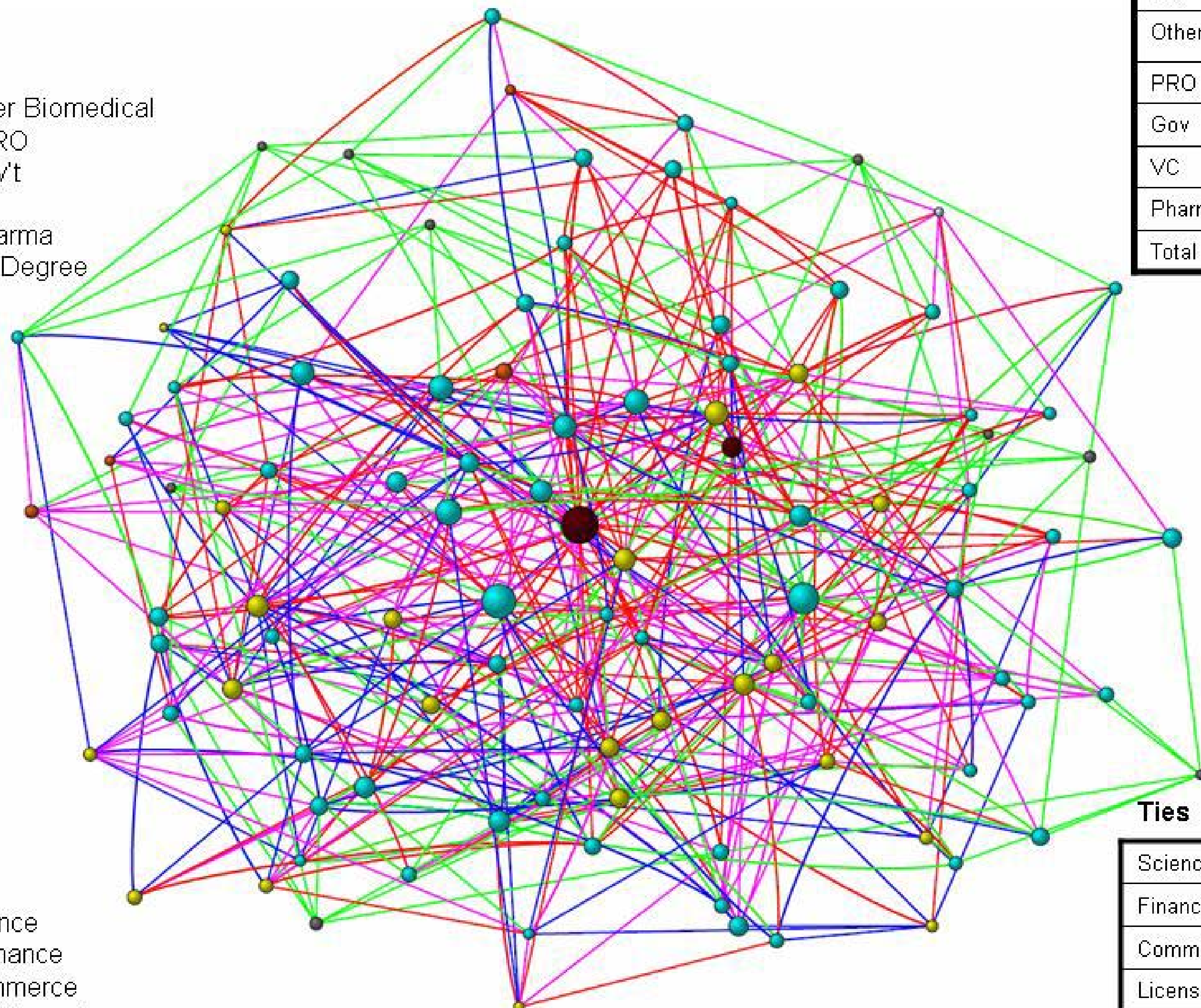
Tie Key
Red = Science
Green = Finance
Blue = Commerce
Magenta = Licensing

Ties

Science	36
Finance	34
Commerce	60
License	34
Total	164

Figure 7. 1998 6-Core, New and Continuing Ties

Node Key
Cyan = DBF
Silver = Other Biomedical
Orange = PRO
Brown = Gov't
Green = VC
Yellow = Pharma
Size = 1998 Degree



Tie Key
Red = Science
Green = Finance
Blue = Commerce
Magenta = Licensing

Nodes

DBF	62
Other	1
PRO	4
Gov	2
VC	9
Pharma	24
Total	102

Ties

Science	256
Finance	143
Commerce	153
License	166
Total	719