TECHNOLOGY SHOCKS, ALLIANCES, AND ORGANIZATIONAL FIELDS: INSIGHTS FROM THE GLOBAL TECHNOLOGY COLLABORATION NETWORK

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ABSTRACT

What does the global technology collaboration network look like, how has it changed over time, and what drove these changes? This study reveals that a spike in alliance activity in the mid-1990s gave rise to a large web that connected a majority of organizations engaged in technology collaboration. However, when collaboration activity plummeted, this web broke apart. I theorize that a major technological shock in IT caused organizations to increase their degree and scope of alliance activity, creating a temporary fusion of organizational fields. Analysis of data on alliances and the growth of the internet and networking technologies supports these arguments.

A rapidly growing body of recent research has suggested that the structure of technology collaboration networks significantly influences important outcomes such as knowledge spillovers, innovation rates, initial public offering success, the diffusion of governance practices, and others (e.g., Powell, Koput & Smith-Doerr 1996; Uzzi, 1996; Ahuja 2000; Gulati & Higgins, 2003; Rosenkopf & Almeida, 2003; Gay & Dousset, 2005; Robinson & Stuart, 2007; Schilling & Phelps, 2007; Gilsing et al., 2008). Nearly all of this research has focused on the industry or organizational field levels of analysis, operating under the implicit assumption that most technology collaboration relationships are struck between firms in the same industry or closely related industries.[1] In so doing, these works have conveyed an image of collaboration networks that are organized into distinct clusters corresponding to industries or organizational fields, that are only sparsely connected together (if connected at all). This is a reasonable assumption – after all, firms in the same industry are more likely to face similar technological challenges and opportunities, and possess knowledge bases that are readily applicable to each other's objectives. They are also more likely to be referred to one another by mutual partners (Gulati & Gargiulo, 1999). The assumption is also a practical one because determining the boundaries of a network is a non-trivial issue, and if network data is to be matched to other covariates (such as financial data or patent data), it may be necessary to constrain the set of organizations examined to those for which data is available.

What if, however, the assumption is wrong? If the network structure does not correlate strongly with the industry or regional boundaries that are used in empirical studies, it would be altogether

[1] For example, Baum, Calabrese and Silverman (2000), Gay and Dousset (2005), Powell, Koput and Smith-Doerr (1996), all focus on biotech firms, and the Baum, Calabrese and Silverman study limits its focus to Canadian biotech firms in particular. Ahuja's (2000) study examined chemical firms in Western Europe, Japan, and the U.S. Schilling and Phelps (2007) examined eleven different industries, but constructed their networks separately, and with a selection method that emphasized U.S. firms.

possible to draw erroneous conclusions. Firms that appear peripheral might actually be quite central in the larger network, or occupy key brokerage positions. Networks that appear to have long average path lengths might, in fact, have very short path lengths – drastically altering the inferences one might draw about the diffusion of information and other resources. And firms that appear to occupy structural holes may actually be embedded in a thicket of unobserved transitive ties, distorting conclusions about how their behavior is constrained or the access they have to nonredundant information. Furthermore, to the degree that we misperceive the structure of the technology collaboration network, we constrain our ability to understand the organizational field(s) that it overlays, potentially leading us to overlook (or misinterpret) institutional pressures that are at work.

Examination of multi-sector alliance databases such as SDC or MERIT-CATI quickly reveals that assuming the network corresponds to industry or regional boundaries is risky. Many technology collaboration alliances span industry and national boundaries, and frequently involve organization types other than firms (e.g., universities, government research laboratories, hospitals, military units). However, without further analysis we could not rule out the possibility that the bulk of alliance activity occurs within industries or regions – the network could, after all, be a loosely coupled system where the most intense interaction is contained within industries, groups of industries, or regions. In such a case, knowing where the breakpoints are between such clusters could be very useful. On the other hand, if the network turned out to be structured as one large, highly centralized web, that would be useful information as well. In general, having at least a rough understanding of the topology of the collaboration network, and a sense of what factors cause structural changes in this network, could greatly improve the decisions researchers make about network research design, the decisions managers make about collaborations to enter, and the decisions policy makers make about their efforts to influence network structure. Thus, in this paper, I analyze the global technology collaboration network to answer three closely related questions: 1. What does the global technology collaboration network look like? 2. How has the global technology collaboration network changed over time, and what drove these shifts? 3. What implications does this network have for understanding the boundaries of organizational fields?

Using SDC technology alliance data from 1990 to 2005, I find that in many years, a very large portion of the organizations engaged in technology alliances are connected into a single large web, and the structure of this network does not correspond to industry or regional boundaries. Instead, there appears to be two primary spheres of technology collaboration – one that is primarily electronics based, and one that is primarily chemical-medical based. Furthermore, the network exhibits some remarkable patterns over time. In the mid-1990s a giant web emerges that is both denser and broader than at any other time during the period observed. This web disintegrates, however, at the end of the 1990s. This network evolution is driven by two closely-related phenomena: 1) a tremendous spike in overall alliance activity in the mid-1990s, and 2) a significant increase in the industry diversification of alliance activity (i.e., organizations forged alliances with other organizations in a much wider range of industries during the mid-1990s than they did either before or after). These dramatic changes in alliance activity went largely undocumented and unexplained in either the scholarly or popular press. These patterns are replicated in multiple alliance databases, suggesting that these trends were a real and important phenomenon that somehow escaped the notice of most observers.

I argue here that the rise of the internet and the concomitant rise in related networking technologies caused a technological shock to the economy. The epicenter of this shock was in the information technology industries, but its reverberations were felt in many industries, and in many layers of the economy. The internet was a “general purpose technology” with the potential to transform information dissemination on a massive scale (Mowery and Simcoe, 2002), creating tremendous uncertainty for organizations. In response, organizations significantly ramped up their technology collaboration activities to pool their knowledge and R&D resources, rapidly access capabilities they did not possess in-house, and create options to exploit new technological opportunities. This is consistent with a large existing body of research that indicates that firms often respond to uncertainty and change by increasing their alliance activity (e.g., Hoffman, 2007; Pfeffer and Salancik, 1978; Powell et al., 2005; Schilling and Steensma, 2001; Stuart, 1998; Uzzi, 1997). However, the data here also indicates that the technological shock prompted firms to greatly increase their formation of collaborations that extended beyond their traditional industry boundaries, increasing the scope of their alliance partners and leading to a fusion of organizational fields – an important finding that refines our understanding of how alliance networks and organizational fields evolve.

These findings have important implications for scholarly work on social and interorganizational networks, technology collaboration and technological change, and the evolution of organizational fields. First, with respect to the work on networks, researchers have noted that there is a paucity of work that examines the longitudinal dynamics of entire networks (Powell, et al 2005). In addressing this gap, I find that environmental uncertainty prompts members of the network to increase both the number of their alliances and the scope of their alliances, significantly impacting the size and density of the network, and leading to the crystallization of a giant web of connected organizations. This event elegantly demonstrates how environmental conditions can induce a phase transition of connectivity -- a phenomenon that is well understood in random graph theory but less often evincible in a social context where connections between members of a network are decidedly non-random.

Second, with respect to the work on technology collaboration and technological change, the data here provide evidence that firms responded to rapid technological change with dramatic increases in collaborative activity rather than large increases in the amount spent on internal R&D. I argue here that because alliances are faster, perceived as more reversible, and not as directly subject to budget constraints as R&D or acquisitions, organizations are likely to use technology alliances as one of their first responses to a major technological shift.

Finally, the results here lend insight into how innovation can transform organizational fields. DiMaggio and Powell define the organizational field as comprising “those organizations that, in the aggregate, constitute a recognized area of institutional life: key suppliers, producers, regulatory agencies, and other organizations that produce similar services or products” (1983: 148). Though the term “organizational field” typically means something broader than an industry (because, for example, key suppliers or complementors are included), they are still usually defined in terms of a recognizable market sector such as biotech or pop music. Furthermore, the interorganizational network is typically assumed to be confined primarily within the boundaries of the organizational field. In fact, the structure of the network is thought to provide valuable information about the organizational field within which it operates (Kenis and Knoke, 2002; Powell et al, 2005). However, just as most network studies have been confined to individual industries or groups of closely related industries, most of the work on organizational fields has been similarly constrained. Though there have been numerous excellent studies of specific organizational fields, including work on how these fields change over time (e.g., Meyer, Brooks and Goes, 1990; Leblebici et al., 1991; Hoffman, 1999; Powell et al., 2005) there has been little work that has attempted to understand how multiple fields overlap, and merge or break apart over time. I find evidence here that large scale innovation in a general purpose technology can induce organizations to reach out beyond their typical organizational field boundaries. In particular, the rapid information technology advances of the mid-1990s caused organizations in a wide range of industries – even those that would have seemed far from information technology in the early 1990s – to seek collaborative relationships with information technology firms, causing the information technology industries to become scaffolding to which the rest of the network attached. In essence, the rise of networking technologies enabled a temporary fusion of once disparate organizational fields.

The first part of the paper is an inductive study that examines what the global technology collaboration network looks like and how it has changed over time. I use SDC technology alliance data to construct the global technology collaboration network. I then use both statistical and graphical analysis to assess its size and structure, patterns in industry and regional membership, and longitudinal dynamics.

The second part of the paper is a grounded theory study. I integrate the findings from part I with prior work on alliances and uncertainty to develop hypotheses about how rapid innovation in a general purpose technology affected organizational alliance behavior, and as a result, the global technology collaboration network. I test these hypotheses using the alliance data and data on growth of the internet and networking technologies. The last section discusses the conclusions, limitations, and implications of the results.

I. THE GLOBAL TECHNOLOGY COLLABORATION NETWORK: STRUCTURE AND DYNAMICS

What does the global technology collaboration network look like, and how has its size and structure changed over time? It would be easy to assume that no single large network exists. Collaboration agreements are difficult and costly to forge and manage. Such agreements can also put firms at risk of having their proprietary technologies expropriated by others. This puts significant constraints on the number of collaboration agreements that firms can sustain, and as a result, the average number of technological collaboration agreements in which a firm engages at any point in time is quite small. This suggests that there may not be a single primary network, but instead a large number of small clusters of firms, with little or no connectivity among those clusters. If this is the case, then the term “network” is somewhat misleading, and measures of the overall network structure are not particularly interesting.

On the other hand, if there is a single large technology collaboration network that connects a significant proportion of the organizations engaged in technology alliances, then the structure of this network might have numerous implications for economics, management, and policy. For example, the structure of the network is likely to influence the flow of information and other resources between firms, directing the diffusion of innovations and facilitating technological spillovers. Recent research in many kinds of networks (e.g., acquaintance networks, computer networks, ecosystem networks, etc.) has demonstrated that the structural properties of networks significantly affect the dynamics of transmission or diffusion within them. For example, the number of links (e.g., acquaintance relationships) connecting a group of people, and the average number of links it takes to reach one person from another (the network's "average path length") are directly related to how far and quickly a contagion such as information, fashion, or disease spreads through the network (Yamaguchi 1994; Watts 1999). If the network of technological collaborations among firms enables dissemination of valuable information throughout the network, then both the size and structure of the overall network may be important determinants of the creation and diffusion of innovations, and the likelihood of technological spillovers.

Constructing the Network

To construct the global technology collaboration network, I use announcements of technological collaboration agreements drawn from Securities Data Corporation's Joint Venture and Alliance database.[2] I included every publicly-announced technology collaboration agreement (joint R&D agreements, cross-licensing agreements, and cross-technology transfer agreements) reported as *completed*[3] between any two or more organizations (including firms, non-profits, government agencies, universities, etc.), from anywhere in the world.[4] Notably, relying on this data source

[2] Previous research has shown that the patterns exhibited in the SDC alliance data are highly symmetric with those exhibited in the MERIT-CATI and CORE datasets. A comparative analysis of five major alliance databases, including SDC, indicated that while most alliance databases are incomplete, the temporal and sectoral patterns are highly reliable. For further details on this comparison please see Schilling, 2009.
[3] SDC reports both *pending* and *completed* announcements; I utilize only those alliances reported as completed here.
[4] Though it is often assumed that the SDC has a heavy bias toward US-based firms, recent research suggests that such an assumption may be unwarranted. In a comparative analysis of the geographic scope of the SDC alliance

limits my analysis to only formally-announced relationships, and likely understates the connectivity of the network that would exist if I were able to incorporate informal collaboration relationships. However, there is a strong correlation between the pattern of formal and information relationships between firms, as informal arrangements often lead to the types of formal agreements that I observe here (Powell, Koput and Smith-Doerr 1996; Rosenkopf, Metiu and George 2001). The data were gathered for the period 1990 to 2005 (inclusive). I chose 1990 as the initial year because information on alliances formed prior to 1990 is very sparse in the SDC database (Anand and Khanna 2000: 300; Schilling 2009). The resulting dataset includes 13,304 total alliances between 13,906 organizations from 105 nations.

Alliances typically last for more than one year, but alliance termination dates are rarely reported. This requires the researcher to make an assumption about alliance duration. I took a conservative approach and assumed that alliance relationships last for three years, consistent with recent empirical work on average alliance duration (Phelps 2003). Other research has taken a similar approach, using windows ranging from one to five years (e.g., Gulati and Gargiulo 1999; Stuart 2000). I created alliance networks based on three-year windows (i.e. 1990-1992, 1991-1993, …1995-1997), resulting in fourteen snapshots of network structure. Each network snapshot was constructed as an undirected binary adjacency matrix (Wasserman and Faust 1994). [5] [6] The

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database versus the MERIT-CATI database (Schilling, 2009), it was found that both datasets report more U.S. participants than participants from any other country, and for both datasets the aggregate for North America is over 1.5 times the aggregate for the next highest region, Europe. The main difference in geographic coverage across the two datasets was that SDC has far more participants reported that are from non-OECD countries (21.48% in SDC versus 3.38% in MERIT-CATI). The non-OECD participants in the SDC database are overwhelmingly Asian, with the leading countries being China, Malaysia, Singapore, Hong Kong, India and Thailand, in that order, and collectively accounting for 17.28% of the country-participant counts.

[5] A binary adjacency matrix is a square matrix with nodes (e.g., organizations) as rows and columns. The entries in the adjacency matrix, x_{ij}, indicate which pairs of nodes are adjacent (i.e., have a relationship). In a binary matrix, a value of 1 indicates the presence of a relationship between nodes *i* and *j*, while a 0 indicates no relationship.

technological collaborations are considered to be bi-directional relationships, resulting in an undirected graph. Multiple alliances between the same pair of firms in a time window are treated as one link.

Ucinet 6.2, a leading social network analysis software package, was used to obtain measures of the structural properties of each of these networks (Borgatti, Everett and Freeman 2002). NetDraw 2.24 was used to generate pictures of the networks (Borgatti, Everett and Freeman 2002). The “spring embedding” feature was used in NetDraw to better visualize how close or far each organization is from the others in the network. This algorithm locates nodes closer to each other if there is a short path length between them, and locates nodes farther from each other if the shortest path between them is long, or if there is no path between them at all. A “node repulsion” feature helps to reduce the likelihood of nodes being located on top of each other, and an “equal path length” feature helps to ensure that the distances between adjacent nodes are commensurate. If a network has one large “component” (a group of nodes that are all connected together) and many pairs or triples of nodes that are not connected to this large component, the algorithm often (but not always) results in the pairs and triples being grouped into a single mass that is separate from the large component. For example, in most of the network snapshots here, there is a single large component that wraps around the graph space, and the pairs and triples that are not connected to this large component form a lima bean-shaped mass in the center of the graph.

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[6] Each matrix reflects the alliances *maintained* within the network as of the end of the focal year. Because alliances often endure longer than one year, constructing adjacency matrices using only alliances announced in the focal year could bias the connectivity of the observed networks downward. Consider the initial year of the panel for the network variables (1992): using only alliances formed in 1992 would not capture the alliance relationships formed prior to, yet maintained through 1992. Data on both pre-sample alliance formation and alliance duration is needed to accurately assess network structure in each of the sample years. Moving three-year windows more accurately reflects the structure of an alliance network in the annual adjacency matrices. Robinson and Stuart (2007) use a similar approach in assessing alliance networks in the biotechnology industry. It is worth noting, however, that using only one-year windows results in very similar network statistics and patterns as those reported here.

When there are multiple large components, or a single large component that has several distinct lobes, the pairs and triples not connected to these components may be pushed out into a ring around the large component(s), or may not exhibit any discernible organization.

Network Statistics and Graphics

Table 1 provides some statistics for the yearly network snapshots. As shown, the average number of organizations participating in the yearly technology collaboration networks from 1990 to 2005 was 3369. The data indicates, however, that there was considerable variation in the number of participants for each year. Participation in the technology collaboration network peaked in the mid-1990s, and then underwent a major decline over the latter half of the 1990s. Comparison of SDC data with other multi-industry alliance databases (the MERIT-CATI database administered by Maastricht University and the CORE database of filings under the NCRA-JV act) indicate that this pattern is not unique to the SDC dataset (see Figure 1). In fact, if biotechnology alliances are omitted from the SDC and MERIT-CATI datasets (the MERIT-CATI data contain a disproportionate number of biotechnology alliances, which skews the temporal patterns in the dataset), the three data series are very highly correlated and collectively achieve a coefficient alpha of .83 and thus would be considered very reliable measures of the temporal variation in alliance activity (Nunnally 1978). As indicated in Table I, for most of the years a large percentage of the firms participating in technology collaboration agreements were connected into a single large component, reaching a high of 58% in the 1992-1994 snapshot. However, the number of alliances dropped precipitously toward the end of the decade, fragmenting the network into many smaller components – in the 1999-2001 snapshot, the percentage of firms connected to the largest component was only 9%.

--------------------Insert Table I and Figure 1 About Here---------------------------

Graphical pictures of the network snapshots provide further insight. Figure 2 provides a graphical picture of the technology collaboration network for each time period. The graphs are color coded by component with the largest component in each graph colored red. These graphs provide a stark visualization of how the dramatic rise and fall of alliance activity in the mid-1990s impacted the overall connectivity of the technology collaboration network. As shown, in the snapshots leading up to the mid-1990s, the main component is growing very large and dense. However, after 1996 there is a marked thinning out of the main component, and in the snapshot for 1998-2000, the main component has fragmented into many smaller components, with the two largest components roughly equal in size (red -- 234 nodes, aqua -- 212 nodes). If we believe that alliance networks are important mediums for the transmission of information and other resources, as has been suggested in recent research (e.g., Gay and Dousset 2005; Robinson and Stuart 2007; Schilling and Phelps 2007), then this fragmentation could handicap a number of economic activities such as innovation and trade.

-----------------------Insert Figure 2 About here----------------------------

These graphs also reveal that the network is not organized into many separate groups that correspond to individual industries or regions. Instead, in many of the graphs in Figure 2, the main component exhibits an interesting bi-lobal shape indicating that there are two main groupings of firms. Closer inspection of the data reveals that there are significant differences in industry representation across the two groups. As illustrated in the four representative snapshots in Figure 3, one group is dominated by electronics-based industries (computer hardware and software, communication equipment and service, transportation equipment, household audio equipment, etc.), which are colored orange in the graph, and the other group is dominated by chemical and medical-based industries (pharmaceuticals, chemicals, health services, medical equipment, etc.), which are colored blue in the graph. This grouping also includes a large concentration of educational organizations (primarily universities), which are colored pink.[7] Scientific instruments firms, coded red, are distributed fairly evenly across the two groups. Organizations not falling into any of these categories (e.g., government, financial services, wholesale and retail, etc.) are coded gray. As the graphs vividly portray, connectivity within each group is much denser than between the groups. If the network is serving as a medium within which information and resources can be sought or exchanged, there is likely to be less exchange between the two groups than within them, and the exchange pathways that exist between the two groupings may be especially vulnerable to disruption if collaborative activity declines in a particular period.

--------------------------Insert Figure 3 About Here-------------------------------

In the graphs for the time periods of 1999-2001 and 2003-2005, only components of five nodes or more are shown for visual clarity. These graphs reveal that after the decline of alliance activity in the latter part of the 1990s, the electronics groupings were often disconnected from the chemical-medical groupings. Previous research has suggested that combining information across highly disparate technical fields can result in breakthrough generative events that lead to innovations of great magnitude (Perkins 1995; Fleming 2001; Hargadon, 2003). The connectivity between the electronics grouping and the chemical-medical grouping might thus have been particularly important for breakthrough innovation, and the separation of these components could have had a deleterious impact on innovation by reducing the range of recombinant possibility.

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[7] The data here indicate that over the time period studied, there were 296 universities engaged in technological collaborations. Some of the universities with the highest centrality indices include Stanford University, Massachusetts Institute of Technology, and Keio University in Tokyo, Japan.

Geographic Representation

As noted previously, the alliances include participants from 105 nations. Figure 4 shows the same network snapshots shown in figure 3, but now color-coded by region. The first point to observe is that organizations from North America (red), Europe (blue), and Asia (green) dominate the graphs, though other regions (gray) are also represented. The second point to observe is that the diagrams provide strong evidence that technology collaboration network boundaries do not typically follow regional boundaries. Though the large component in the first two diagrams is dominated by North American-based organizations, there are also large numbers of European and Asian organizations in the component, often in very central positions. Even in the more fragmented networks that follow the decline of alliance activity, components that are circumscribed by a single region are the exception rather than the rule. This suggests that alliance studies that limit their focus to firms from a single country or continent are likely to dramatically understate the connectivity of the network.

------------------------------Insert Figure 4 About Here -------------------------------

II. TECHNOLOGY SHOCKS AND ALLIANCE BEHAVIOR

What could have driven such dramatic changes in the global technology collaboration network? In this section, I argue that alliances are one of the first ways that firms respond to uncertainty and environmental change, as when a major technological shock impacts their industry. I provide some evidence that just such a shock caused the changes in the network detailed previously, and show how the impact of this shock rippled through other layers of the economy.

Alliances as a Response to Uncertainty

Alliances are one of the key ways that firms respond to uncertainty and rapid environmental change (Pfeffer and Salancik, 1978; Gulati, 1998; Powell et al., 2005). First, firms often use alliances to gain access to information and critical capabilities they lack in-house (Schilling and Steensma 2001). For example, firms might make probing alliances with a range of partners to find out about new developments and establish options to pursue different technological directions (Hoffmann, 2007). Through an alliance, a firm can establish a limited stake in a venture that enables it to learn about a new technological opportunity, while maintaining the flexibility to either increase the commitment at a later date or shift these resources to another opportunity (Kogut, 1991; Mitchell and Singh, 1992; McGrath, 1997; Wadhwa and Kotha, 2006). Second, alliances enable firms to pool their R&D funds, complementary skills, and other resources in order to jointly create new technologies faster than they could do so alone. R&D budgets are relatively inelastic – they are often constrained by cash flows and arduous budget approval processes. [8] Pooling their resources helps firms to overcome this constraint, enabling them to mount a larger response to a technological opportunity, and share the risk of the venture. Third, alliances enable firms to plan a coordinated response to an environmental change, and thereby influence its impact. For example, during the mid-1990s, many firms formed alliances to build coalitions around particular IT standards in efforts to control which technologies would rise to the position of dominant design. Alliances are thus a way that firms attempt to regain some control over a changing environment.

Though a large technological shock can lead to many long-term changes in organizational form and the organizational field, I argue here that alliances will often be one of the *first* ways that

[8] Most firms allocate a fixed percentage of the previous year's sales to R&D with very little slack allowed for emergent opportunities. Even in the longer term one sees relatively little variation in the amount of R&D spent as a percentage of sales in established firms.

organizations respond because they are perceived as faster, lower cost, and more reversible than internal development or acquisition. Large spikes in alliance activity might thus provide advanced notice of future trends in other economic indicators.

A Shock in Technological Opportunity

Examining the sectoral decomposition of SDC alliances in Figure 5 indicates that IT firms figured prominently in the alliance spike of the 1990s. Of the five sectors that appear to contribute most significantly to the mid-1990s peak, four are central to information technology: Electronics and electrical equipment (which includes both semiconductors and telecommunications equipment); business services (which is heavily dominated by software); industrial machinery (which includes computers); and communications services. Two other sectors that standout during this time period are chemicals (primarily pharmaceutical and biotech alliances), and engineering and management services (which is dominated by management consulting and biological research services). A count of the alliances by *primary activity* (based on SDC's classification of alliance activities into SIC codes) reinforces this observation about the role of IT. The percentage of alliances that were formed primarily for information technology activities (computer equipment 3571-3577; communication equipment 3661-3669, semiconductors and related components 3671-3679, communication services 4812-4899, software 7371-7379) rose from 26% in 1990 to a peak of 58% in 1995, then dropped sharply.

----------------------------Insert Figure 5 About Here---------------------------------

It is not hard to identify sources of turbulence in information technology industries in the early and mid-1990s. Personal computers and cell phones were rapidly penetrating the mass market, and several standards battles were being played out in technologies such as microprocessors, collaboration software, and operating systems. However, probably the most iconic change in information technology in the 1990s was the dramatic rise of the internet. The internet is a "general purpose technology" that transformed information dissemination and exchange in nearly every industry of the economy (Mowery and Simcoe, 2002). Though its origins were created in 1969 by the U.S. Department of Defense, it was primarily a tool of science and education throughout the 1970 and 1980s -- its reliance on text-based programs limited its commercial appeal. This was exacerbated by the fact that commercial use of the ARPANET backbone was forbidden. However, by the early 1990s the network had grown well beyond the constraints of the original ARPANET backbone; other government institutions and commercial providers had built their own backbones and regional network access points had become the primary interconnections between networks, ending any limitations on commercial use. In 1993, a program called Mosaic introduced a graphic interface to the network, and the internet began to attract the widespread attention of business and media. Traffic on what was now called the World Wide Web grew explosively, unleashing a frenzy of business activity directed at leveraging the internet. At the same time, rapid advancements in semiconductors, networking hardware, and software enabled dramatic increases in the capacity and speed of the internet (Mowery and Simcoe, 2002).[9] As shown in Figure 6, the early 1990s were pivotal turning points for the internet. In 1993, internet penetration of the U.S. market surpassed three percent, moving from the "innovator" segment of the market to the "early adopter" segment of the market (Rogers 1995), and the number of internet hosts was rising exponentially. The sea change that was underway is illustrated by the stark contrast in the following quotes, only two years apart: "*Let's face it. Not many members of the public -- even the computer literate public - are on the Internet"* (John Goodwin, Email 101, a tutorial for the internet, in July of 1993).

[9] Please see Mowery & Simcoe (2002) for a more complete discussion of the history of the internet.

"*Businesses and entrepreneurs are rushing into cyberspace like forty-niners driven mad by gold fever*" (Vic Sussman and Kenan Pollack, *U.S. News and World Reports*, November of 1995).

-----------------------------Insert Figures 6 and 7 About Here----------------------------

Figure 7 shows a) the number of new alliances that had at least one partner in the information technology industry, b) the multifactor productivity growth for the semiconductor industry (whose advances were primarily responsible for the rise of both the internet and personal computers), and c) the yearly growth rate of internet hosts. The series are very highly correlated (IT alliances and growth in internet hosts, .62, $p<.01$; IT alliances and semiconductor multifactor productivity growth, .52, $p<.01$; semiconductor multifactor productivity growth and growth in internet hosts, .40, $p<.01$). The standardized items collectively achieve a Chronbach's alpha of .76, suggesting that they could be considered multiple measures of the same underlying construct.

The preceding suggests that there was a massive surge in alliance activity by organizations in the information technology industries that was, at least in part, undertaken as a response to the uncertainty and opportunity unleashed by the internet. The transformation of the global technology network was more, however, than just a response of information technology firms to an information technology opportunity. If the bulk of the alliances in the mid-1990s peak had been between pairs of information technology firms, we might have expected to see a very dense information technology network component emerge that was only loosely coupled to the rest of the network. This is not what happened. Figure 8 shows a sectoral decomposition of the SDC alliances with the information technology, chemicals, and engineering and management service sectors removed. It is readily apparent from this graph that the mid-1990s alliance spike affected a wide range of industries – including (in roughly descending order) wholesale trade, financial services, instruments, transportation equipment, metals and fabricated metal products, printing and publishing, utilities, mining and more.

--------------------------------Insert Figure 8 about here---------------------------------

The technological shock of the internet created a wave of uncertainty and opportunity that rippled through many industries – not just those most typically associated with information technology. There was significant uncertainty in how the internet and associated networking technologies would transform an industry's business models. It would disintermediate some value chains while creating new intermediaries in others. It would enable major changes in how organizations communicated both internally, and externally with customers and suppliers. The net result would be significant industry churn that could cause once dominant organizations to be displaced by competitors that made better gambles about how to exploit the new technologies. To deal with all of this uncertainty, firms not only formed more alliances, but may have reached out beyond their typical alliance partners, blurring the boundaries of traditional organizational fields. In particular, many organizations might have sought to form relationships with information technology firms in order to access information and capabilities that would help them respond to – and benefit from – the rapid advances in networking technologies. Though previous work has emphasized the self-reinforcing nature of alliance networks due to the benefits of learning through repeated partnerships and referrals from common third parties (Uzzi 1997; Gulati and Gargiulo 1999; Anand and Khanna 2000; Goerzen 2007), such processes can cause the network resources to become homogeneous and redundant (Burt 1992; Granovetter 1973). When solutions are needed to a fundamentally new kind of problem, the repository of knowledge within the network about both solutions and prospective partners may be inadequate. Firms may need to seek partners well beyond the boundaries of their existing networks. If the preceding is true, then the we may be able to identify an association between the rapid growth of the internet (and related networking technologies) and either a) the scope of alliance activity undertaken by both IT firms and organizations in non-IT industries, b) the percent of alliances formed with IT firms by organizations that are not in IT industries, or both. I thus test the following hypotheses:

> **Hypothesis 1**: The growth rate in the internet and related technologies will be positively associated with the scope of alliance activity by organizations in both information technology and non-information-technology industries.
>
> **Hypothesis 2**: The growth rate in the internet and related technologies will be positively associated with the percent of alliances formed with IT firms by organizations in non-IT industries.

Finally, if organizations from a wide range of industries began to form alliances with firms in information technology industries, the information technology industries could have become the linchpins that connected disparate portions of the global technology network. To explore this possibility, I will graphically examine the effect of removing IT firms from the network.

METHODS

To test the hypotheses above, I will combine the alliance data described earlier with a composite index of the yearly growth rate of the internet and related technologies. The specific measures are defined as follows:

Internet and networking growth index. To capture the growth rate of the internet, I use the yearly percentage increase in internet hosts. To proxy for growth in networking and related technologies I use the yearly change in semiconductor total factor productivity as advances in semiconductors were one of the most important factors underlying advances in networking. As noted previously, the growth rate of internet hosts and the total factor productivity growth in semiconductors are highly correlated. I thus standardized each measure and added them together to create a single yearly index of the growth rate of the internet and networking technologies.

Scope of alliance activity. To measure the scope of alliance activity, I first calculated a Herfindahl-Hirschman Index (HHI) of the industries with which organizations in the target industry have formed alliances:

$HHI = \Sigma\ p_{ij}^2$

where p_{ij} is the percentage of target industry *i*'s alliances that are formed with partners in industry *j*. The maximum value this measure can take is 10,000 (where all of industry i's alliances are formed with the same industry j – this is most likely to happen when i = j, i.e., organizations only make alliances within their own industry). I then inverted this measure by dividing 10,000 by the resulting HHI in order to create an increasing measure of scope. Industries are measured at the two-digit level, and the measure is calculated yearly.

Percent IT alliances. This is a yearly measure of the percent of an industry's alliances that are formed with partners in IT industries.

To examine the role of IT firms in connecting the global technology network, I will compare two representative snapshots from the peak alliance years (1994-1996, and 1996-1998), before removing IT firms and after removing IT firms. As a conservative test, only firms in those industries most closely associated with information technology will be removed (computer equipment 3571-3577; communication equipment 3661-3669, semiconductors and related components 3671-3679, communication services 4812-4899, software 7371-7379).

RESULTS

Table 2 shows the descriptive statistics and correlations for the measures for the pooled sample (all industries), and for split samples: IT industries and non-IT industries. Table 3 shows fixed-effects panel regressions for each of the dependent variables (alliance scope, and percent IT alliances) for each of the three samples. For each of the dependent variables I first ran a restricted model with industry dummies to control for industry fixed effects, and then ran the full model so that the change in R squared due to addition of the internet and networking growth index could be assessed. Hypothesis one posited that the scope of alliance activity for both IT industries and non-IT industries would be positively related to the internet and networking growth index. The results indicate positive and significant relationships between alliance scope and the internet growth rate index for the pooled sample and for the non-IT industries subsample. There is not, however, a significant relationship between alliance scope and the internet and networking growth index for the IT industry subsample. I will return to this result in a moment. Hypothesis two posited that the percent of alliances formed with organizations in IT industries would be positively related to the internet and networking growth index. The results for all three samples indicate strong support for this hypothesis ($p<.01$ for the pooled sample and non-IT sample; $p<.05$ for the IT sample). These results shed some light on the mixed results for Hypothesis one. The results indicate that even though the rapid growth in internet and related technologies lead non-IT firms to form alliances with IT firms (and thus, reciprocally IT firms were forming alliances with non-IT firms), IT firms were simultaneously forming an even greater number of alliances with other IT firms, dampening the alliance scope effects.

----------------------Insert Tables 2 and 3 Here--------------------------------

Finally, I graphically explore the degree to which alliances with IT firms were responsible for the crystallization of the giant component that emerged during the mid-1990s. Figure 9 shows the network snapshot for 1994-1996, in which the main component was particularly large and dense due to the spike in alliance activity. As shown, the removal of the IT firms results in a marked thinning of the upper lobe of the component (the portion that was previously identified as being dominated by organizations in industries that fundamentally rely on electronics). Only the red nodes are those that remain a connected component – more than half of the upper lobe is no longer a connected a component, indicating that the removal of the IT alliances causes a partial disintegration of the electronics-based network lobe. The results are even starker for the 1996-1998 snapshot (Figure 10). In this year, the demarcation between the two lobes of the network is particularly clear. While the removal of the IT firms has little impact on the chemical-medical based lobe, it is devastating for the electronics-based lobe. The electronics-based lobe not only becomes much less dense, but it also shatters into much smaller components.

----------------------------Insert Figures 9 and 10 About Here-------------------------------

Overall, then, the results indicate strong support for the argument that rapid innovation in information technology during the mid-1990s dramatically influenced alliance behavior, including the degree of alliance activity, the scope of alliance activity, and the target of alliance activity. This alliance behavior, in turn, led to a remarkable rise, and then decline, of the global technology collaboration network. More generally, the results provide support for the argument that a major technological shock (or other source of intense uncertainty) can prompt firms to both intensify their collaborative activity, and seek collaboration opportunities outside of their typical industries or value chains, causing a blurring of organizational field boundaries.

DISCUSSION

This paper was motivated by some fundamental questions about the global technology collaboration network: Is there a single large global, multi-industry network connecting a large proportion of organizations engaged in technological collaboration? If so, what does it look like? How has it changed over time, and what drove those changes? Furthermore, what insight does it provide for understanding organizational field boundaries? The first part of the paper was an inductive study that revealed that in the mid-1990s, a significant spike in alliance activity led to the emergence of a very large connected web of organizations. At its peak, this web connected 58% of all organizations (from any industry, and from any nation) that had public technology alliance announcements that were reported by SDC. Visual examination of this component suggests that rather than each industry having its own network, as has been commonly implied in the existing research, there were two main groups of industries: one that contained electronics-related industries and one that contained chemical and medical-related industries. Organizations from other industries (e.g., wholesale, retail, financial services, printing and publishing) appeared in both groups and exhibited no discernible pattern. There was also no discernible segregation of organization types or regions. Even when this giant component disintegrated into many smaller components toward the latter half of the 1990s and early 2000s, it did not break into fragments that corresponded to unique industries, organization types, or nations. This suggests that network analyses that restrict their examination to only those organizations of a particular type (e.g., firms) or from a particular industry or nation are at risk of significantly underestimating both the size and connectivity of the network. This does not immediately imply that results from more narrowly defined network analyses are incorrect – it is altogether possible that many tests based on microcosms of the technology network will yield symmetric results to those based on a more broadly defined network, much like the self-similarity of fractals. It does, however, suggest that studies of industry networks or networks constructed of a particular organizational type, for example, should consider the influence of a broader scope of embeddedness.

The inductive study also indicated that the network had undergone dramatic changes. A sharp spike in alliance activity in the mid-1990s led to the rise of a giant component, and a precipitous drop in alliance activity in the latter half of the decade caused the component to disintegrate. Sectoral decomposition of these temporal trends revealed that information technology industries played a central role in the alliance spike, however the results also indicated that many other industries, including those not typically associated with information technology, also exhibited sharp increases in alliance activity in the mid-1990s. These findings led to the grounded theory study in the second part of the paper that attempted to assess what caused these major changes in alliance activity.

Integrating the findings from the inductive study and prior research on alliances, I theorized that technology alliances are one of the primary – and early – ways that organizations respond to uncertainty and environmental change. This indicates that large spikes in alliance activity could serve as an early indicator of a technological shock in the environment. It is worth noting that while the information technology bubble and crash were readily observable and well documented, the spike and crash in information technology alliances occurred almost *five years* *earlier*. Figure 11 shows a graph of standardized potential indicators of the tech bubble, including patents with the word "internet" in the text (by application year), the number of times the word "internet" appeared in the *Wall Street Journal*, sales and R&D figures for computer hardware and software firms, and U.S. acquisitions of information technology firms. [10] None of these indicators would have given advance notice of the peak and crash. Monitoring semiconductor total factor productivity growth would have given alert, but this data is usually only available with one or two years lag. Monitoring the growth rate of internet hosts would also have given early warning, though this data was only erratically available until several years later and would have required insight into the nature of the underlying phenomenon (i.e., one would have needed to suspect that there was a boom in internet activity specifically). Alliance data, however, can be tracked daily, and can exhibit patterns without the observer first specifying a particular technological focus. It is thus possible that spikes in alliance activity could provide a valuable early warning system for identifying technological volatility whose impacts will ultimately reverberate through other layers of the economic system.

---------------------------Insert Figure 11 here-----------------------------------

As noted, sectoral decomposition of the technology alliance data indicated that the spike in alliance activity was significantly more pronounced in the information technology industries than in other industries, providing a clue that the shock might have been most directly related to information technology. Though there were several major trends occurring in the information technology industries (including increasing sales of both personal computers and mobile phones), the most obvious contender was the internet. Consistent with this intuition, a set of data series on the number of internet users, the number of IP hosts, and total factor productivity in

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[10] The NCRA CORE data were used in this figure rather than SDC since the data in the CORE database are reliably reported as early as 1985 (Link, 1999).

information technology industries indicated that dramatic increases in each of these indicators occurred just before the rise in alliance activity. I thus posited that rapid advances in internet and related networking technologies had created a technological shock in the environment whose epicenter was in the information technology industries but whose effects rippled through many industries – even those not typically associated with information technology. To respond to the opportunity and uncertainty, firms increased not only their degree of alliance activity, but also the scope of their alliance activity. Reaching out beyond their typical partners, they created a temporary fusion of organizational fields. Many non-IT firms sought alliances with IT firms, causing the IT industries to become linchpins that held disparate portions of the network together. Fixed effect panel regressions and graphical analysis largely supported these hypotheses, with the exception that information technology industries did not exhibit increased scope of alliance activity. They increased formation of alliances both with other IT firms and non-IT firms, making the net effect on scope insignificant.

The data used here is limited in some respects. Though a much broader range of alliance data was used here than is typical of the ex-ante research (including data on any type of organization, from any industry, and any nation), it is still limited in that it relies on public announcements of collaboration agreements in the SDC database. Like all alliance databases, this database is incomplete. Furthermore, it neglects informal collaboration agreements. Previous research has shown that the temporal and sectoral patterns in the SDC database are highly reliable despite this incompleteness (Schilling, 2009), but it remains that our understanding of the global technology collaboration network could be refined by more exhaustive databases of both formal and informal collaboration agreements.

Despite its limitations, the research offers a number of important contributions. First, it provides unique insight into what the global technology collaboration network looks like. As the old proverb about three blind men and an elephant alludes, it can be very helpful to have a sense of what the whole animal looks like. Overall, the results suggest that organizations involved in technology collaboration of any kind might be significantly more connected than previous studies would suggest. It also revealed that the world of technology collaboration operates primarily in two distinct spheres corresponding to electronic-based organizations and chemical-medical based organizations. Though in retrospect it may not be surprising that the network can be divided into two major groupings, it is interesting information about the structure of the industrial collaboration landscape that was previously unknown. Understanding this structure might help policy-makers make better-informed decisions about investments that encourage technological innovation, and help researchers to make better informed decisions about designing network studies.

Second, the research here indicates that the global technology network does not adhere to regional boundaries. This raises important questions such as “to what degree do structural features of the collaboration network determine (or reflect) the flow of information and other resources between nations?” It would be interesting, for example, to examine whether the pattern of collaboration activity between nations is an antecedent or outcome of trade, and whether a nation’s position in the overall network influences its future prosperity.

Third, the data indicates that patterns in alliance activity may provide an early signal of a technological shock: A major change in technological opportunity triggers vigorous alliance activity as firms scramble to assess the scope of the opportunity and assemble knowledge and other capabilities required to respond. R&D investments and other irreversible commitments do not come until later, when the technological shift becomes better understood. Ultimately, the technological opportunity is likely to influence patent applications, new product announcements, and other economic outcomes. This suggests that tracking alliance activity may be a valuable way of gaining early notice of peaks and valleys in technological opportunity, which, in turn, can help investors and policy makers anticipate other economic outcomes.

Finally, the results indicate that a shock in technological opportunity can have a profound effect on the types of partners with whom organizations choose to forge alliances. While previous work has emphasized the self-reinforcing nature of alliance networks (Gulati, 1998; Gulati and Gargiulo, 1999; Goerzen, 2007), the results here show how a major technological shock can disrupt these patterns. When firms face new types of problems, they may seek new types of partners. This has direct implications for understanding the evolutions of organizational fields. As discussed, previous studies suggest that an organization's alliance network represents the organizational field in which it operates. If this is true, the results here suggest that a major technological shock can cause the boundaries of organizational fields to shift and blur, exposing firms to new competitive and institutional pressures.

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Figure 1: Number of Alliances Reported in the SDC, CORE, and MERIT-CATI Databases (Biotech Omitted), Standardized, 1990-2005

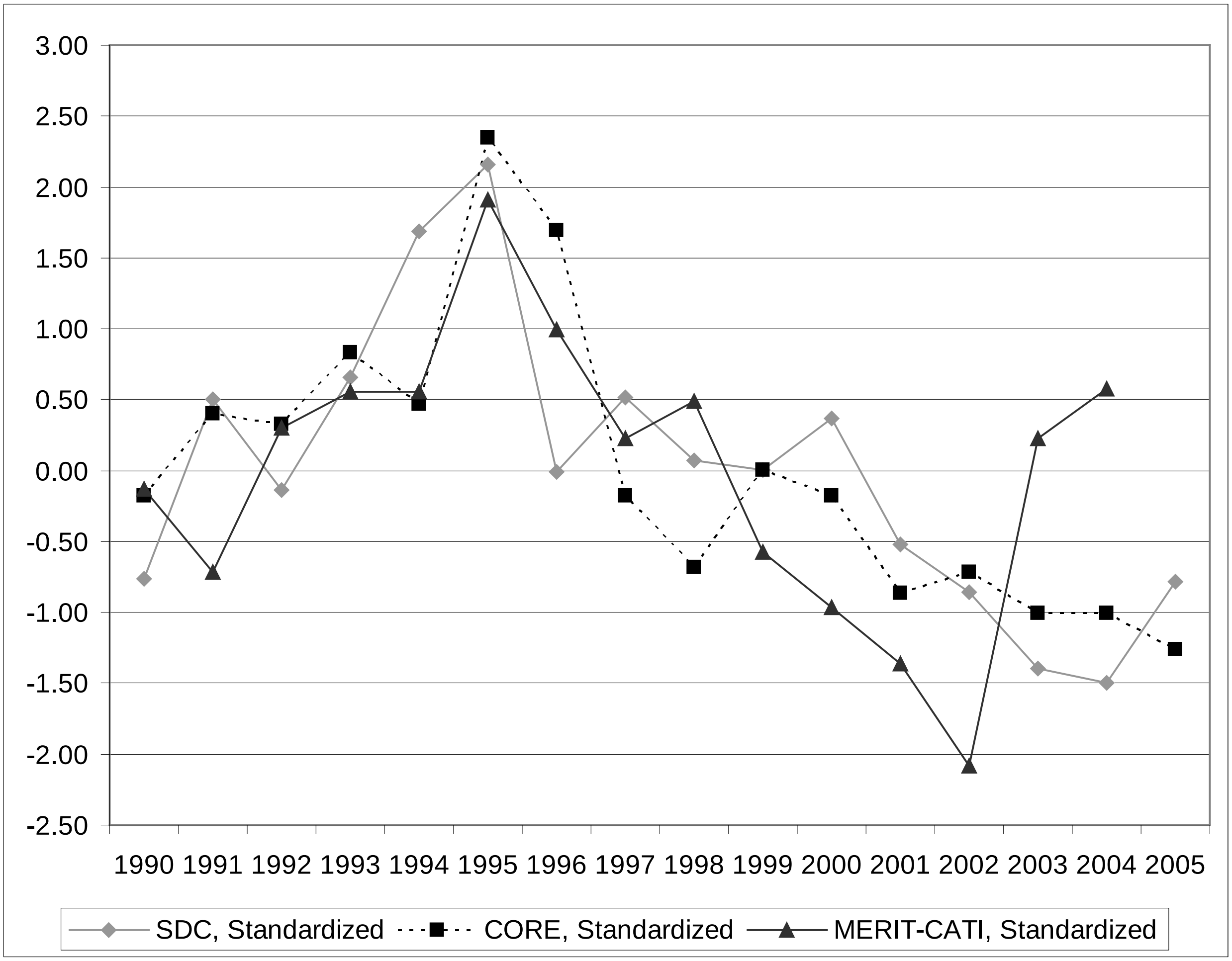
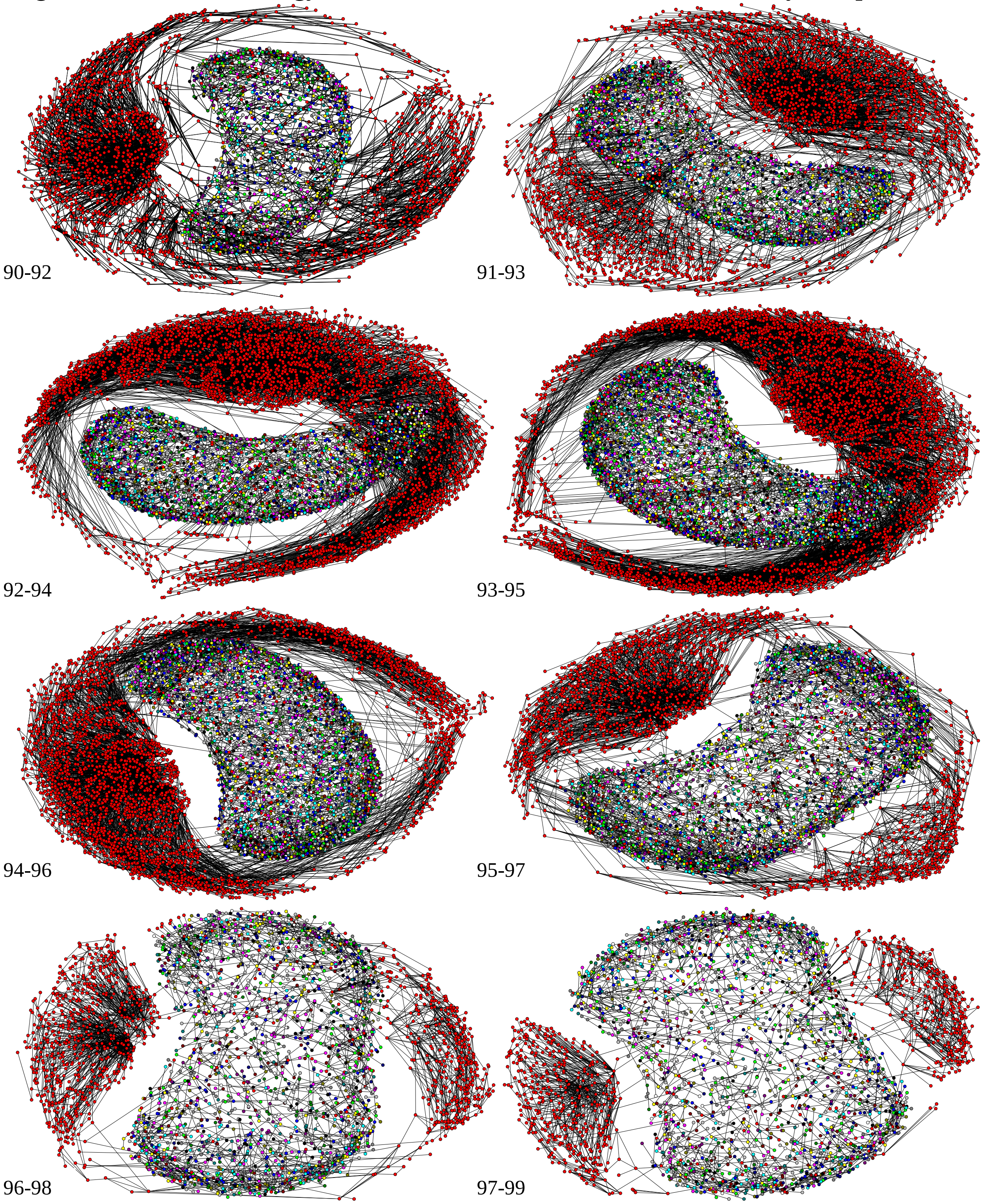
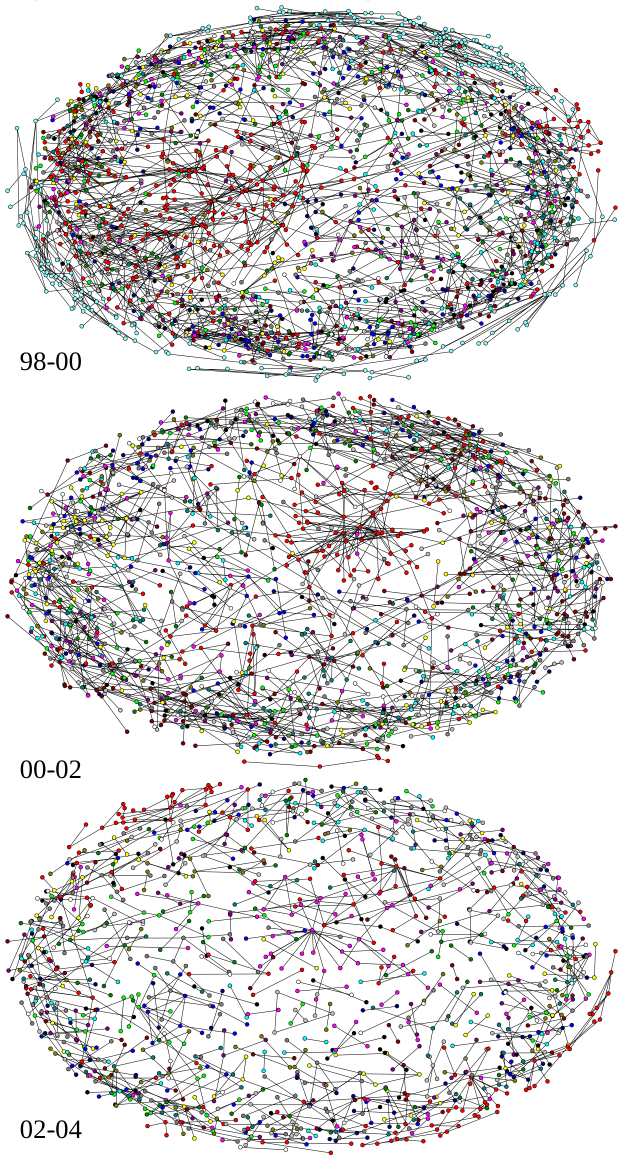


Figure 2: Global Technology Collaboration Network, 1992-2005, Color by Components[11]



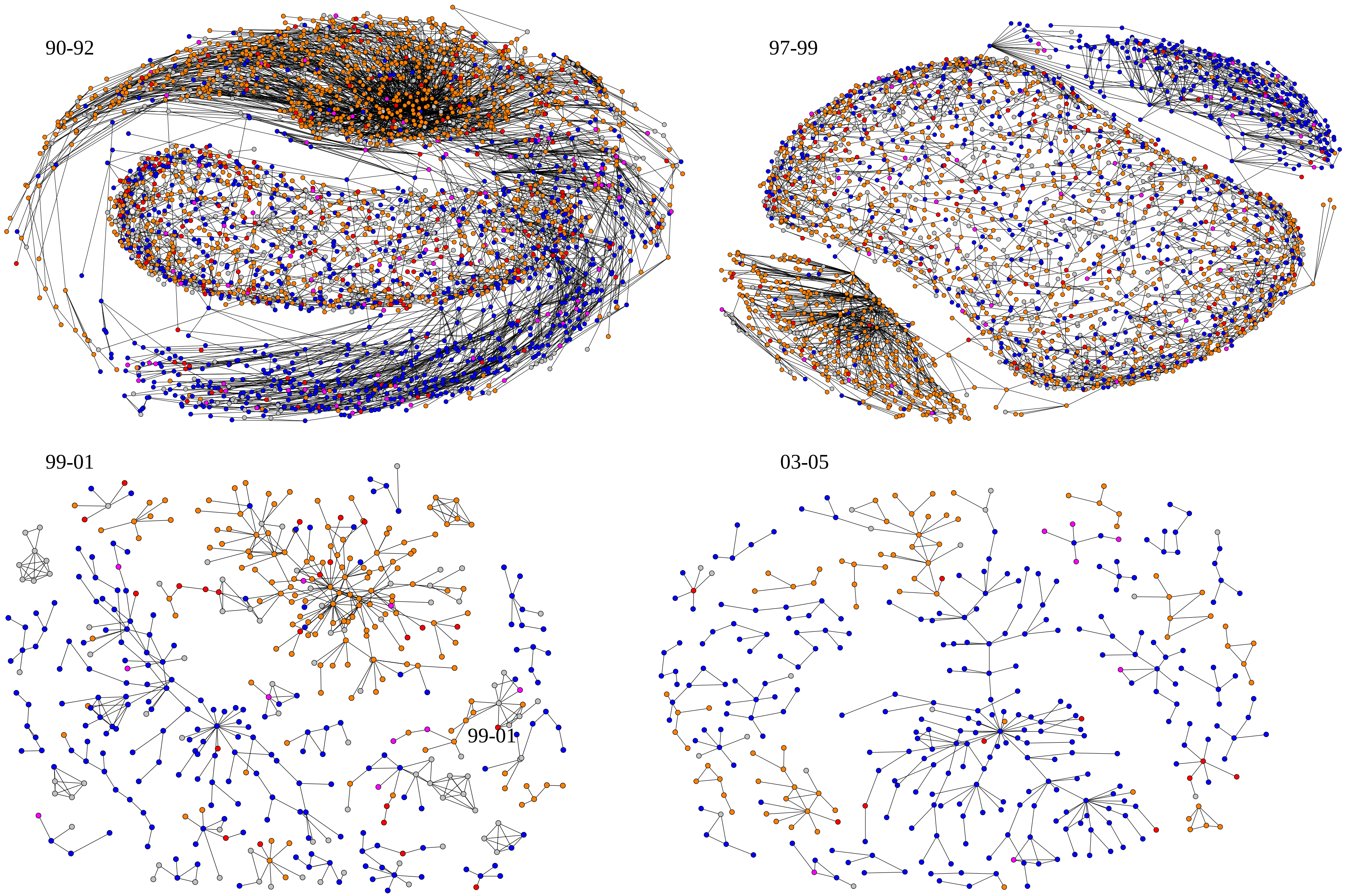
[11] Red indicates largest connected component.

Figure 2: Global Technology Collaboration Network, 1992-2005, cont'd[12]



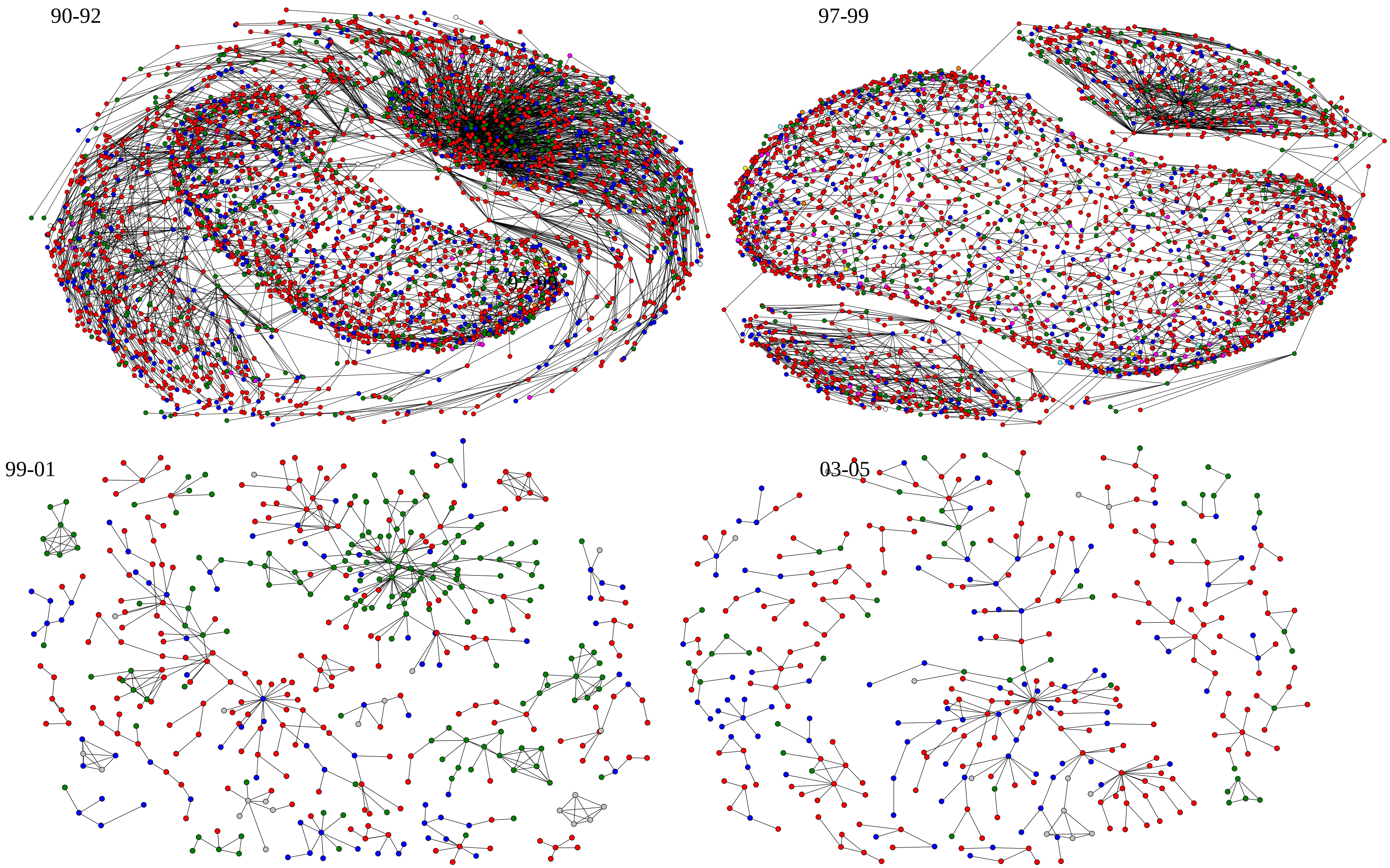
[12] Red indicates largest connected component.

Figure 3: Global Technology Collaboration Network, 1992-2005, Color by Industry Groups[13]



[13] Orange indicates electronics-based industries; blue indicates chemical and medical-based industries; pink indicates universities; red indicates scientific instruments

Figure 4: Global Technology Collaboration Network, Color by Continent[14]



[14] Red indicates North American organizations; blue indicates European organizations, green indicates Asian organizations, gray indicates other regions.

Figure 5: Sectoral Decomposition of SDC Alliances, 1990 - 2005

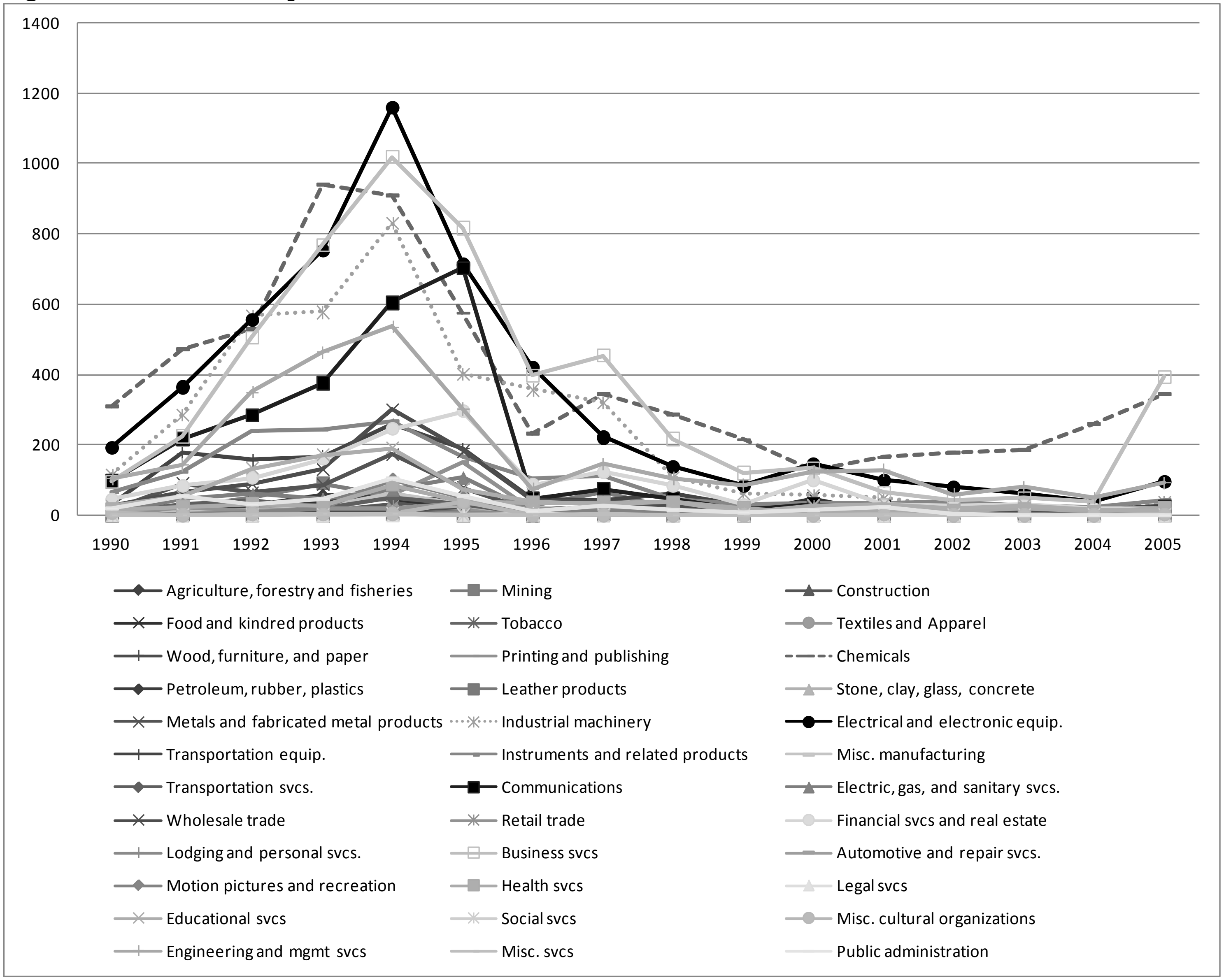


Figure 6: Penetration of the Internet: Percent of US Population using the Internet, and Number of Internet Hosts

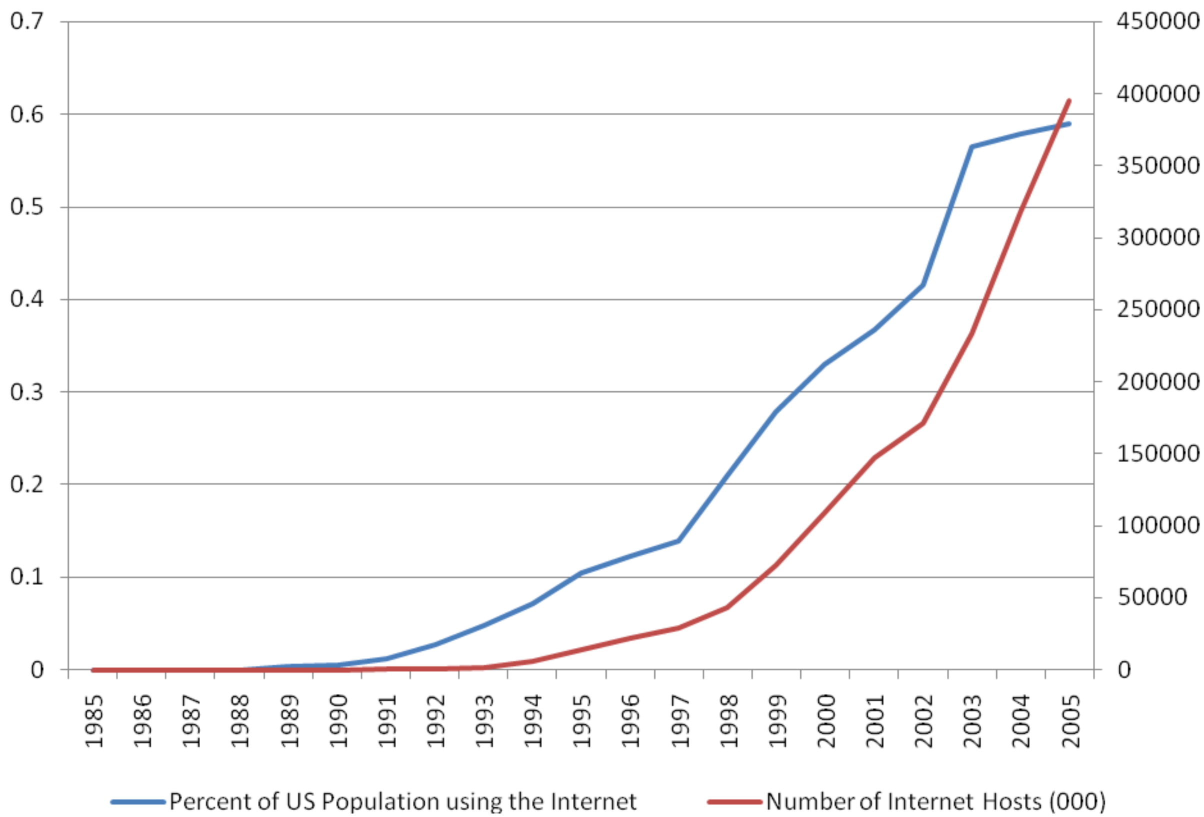


Figure 7: IT Alliances, Growth in Internet Hosts, and Multifactor Productivity Growth in Semiconductors

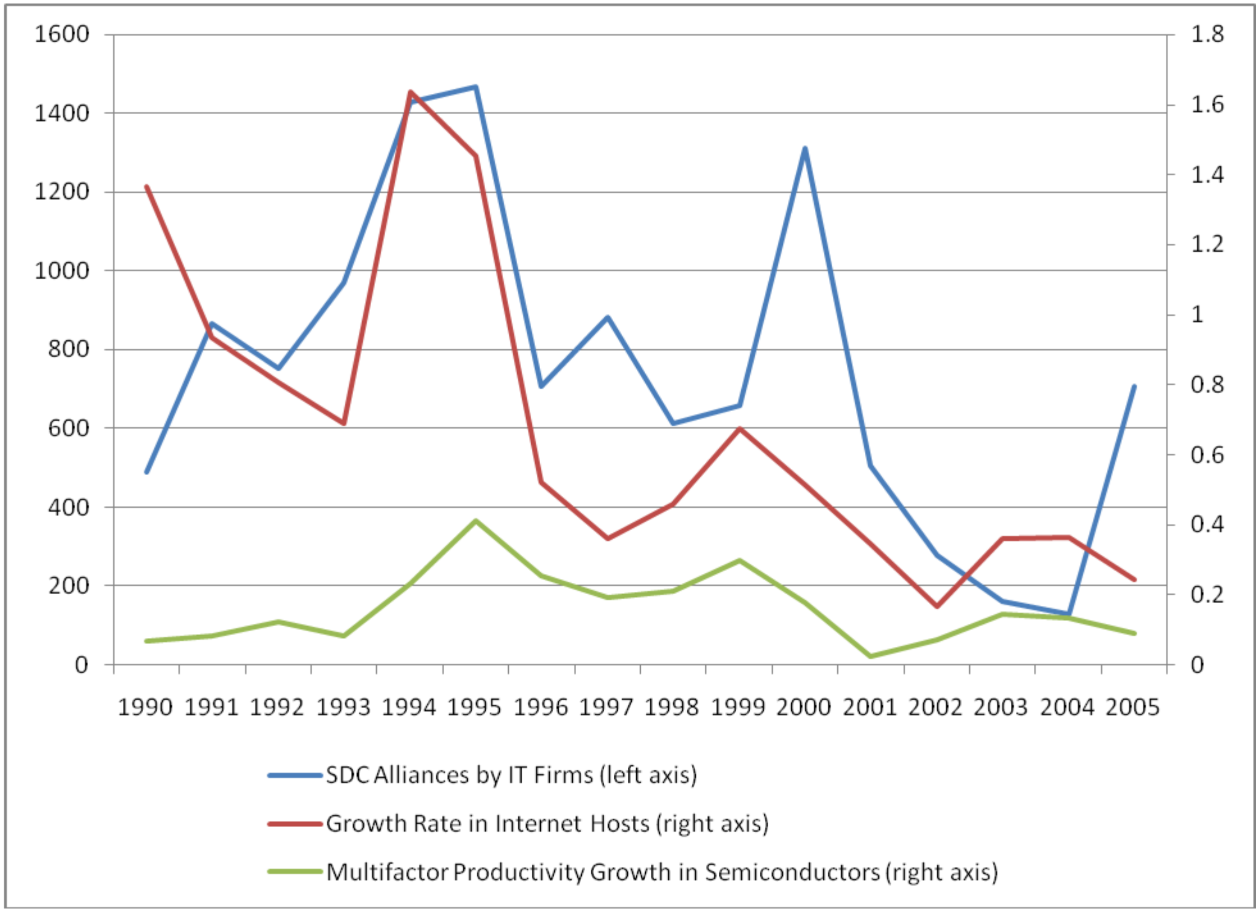


Figure 8: Sectoral Decomposition of SDC Alliances Omitting Dominant Sectors, 1990-2005

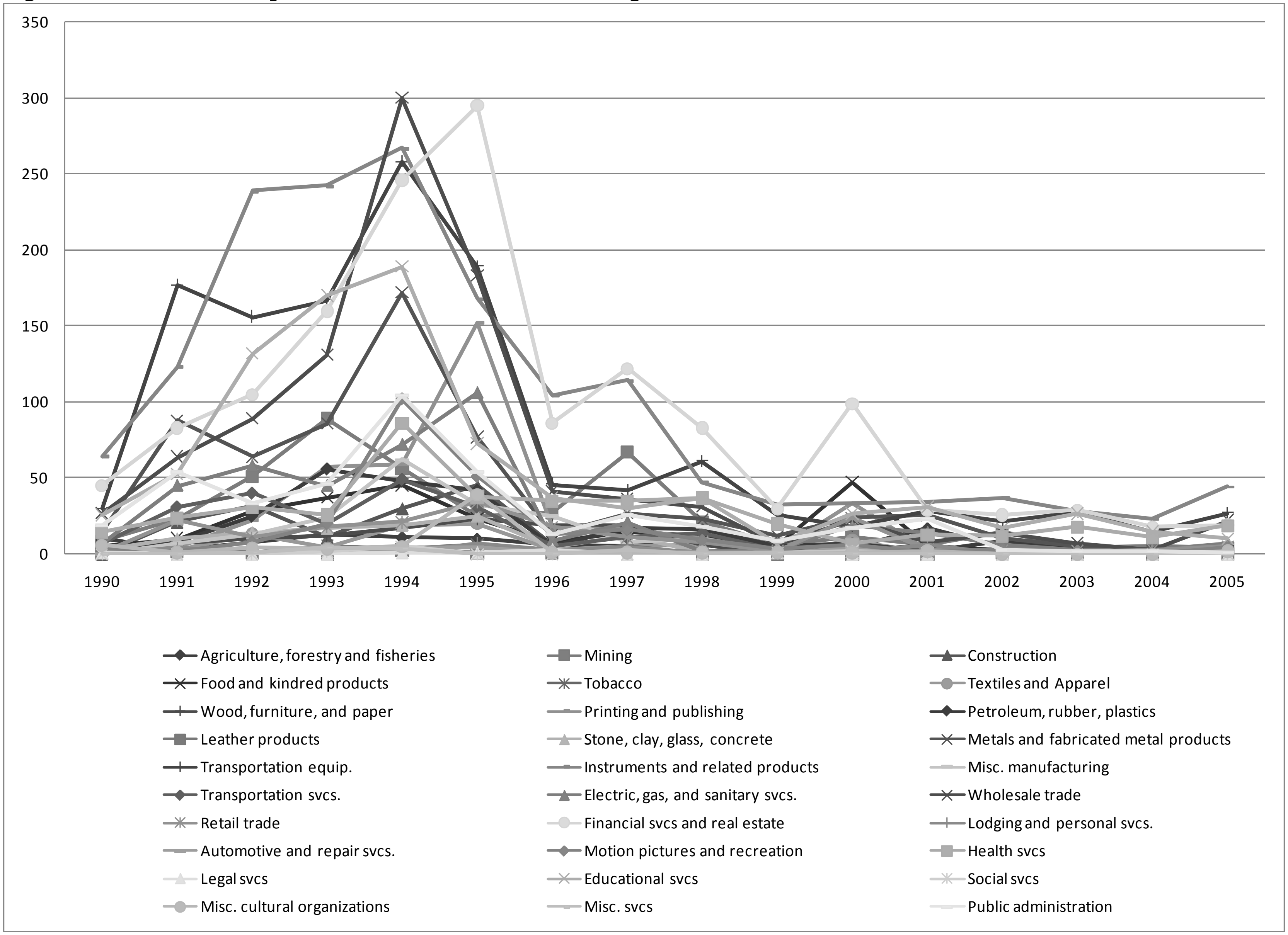
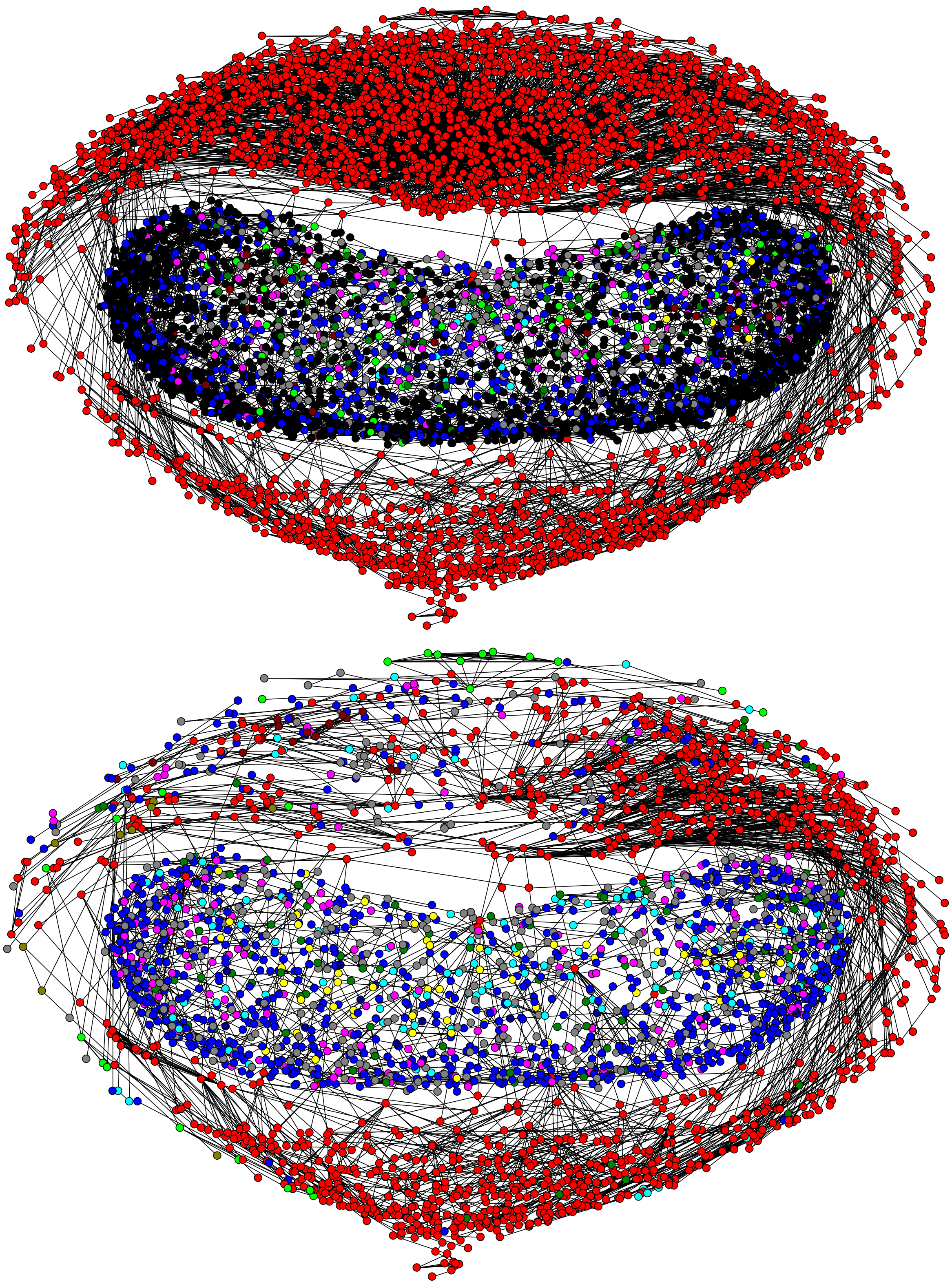
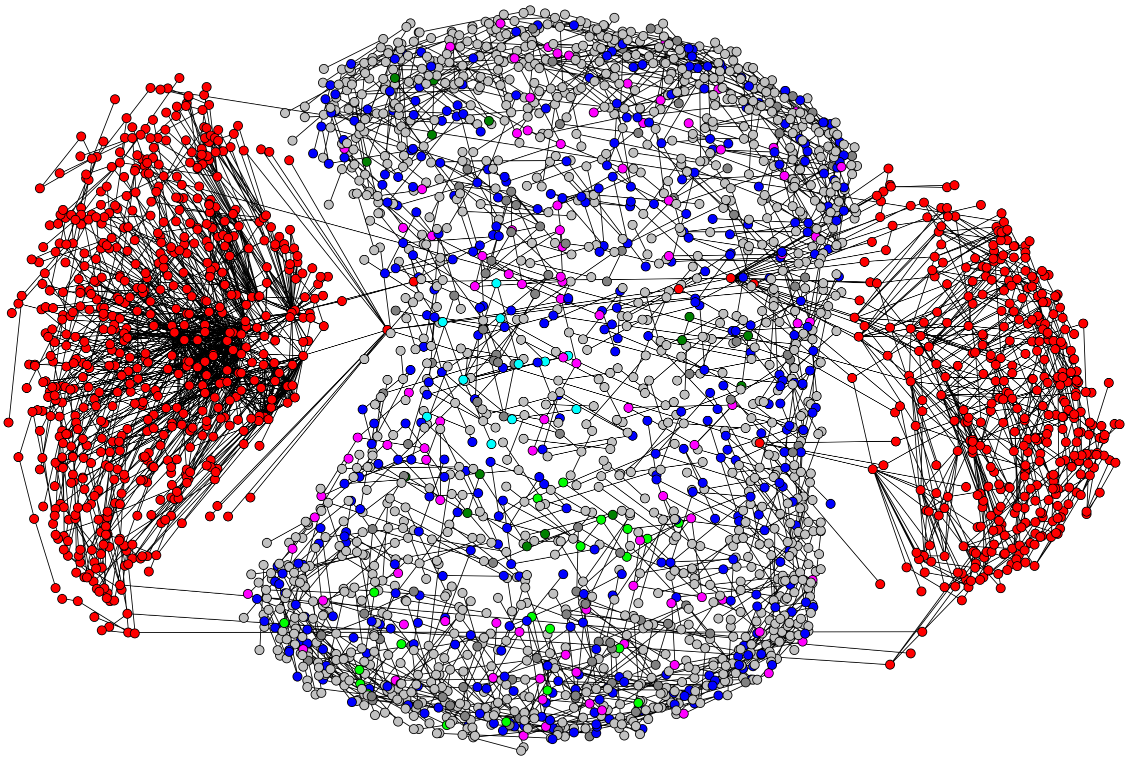


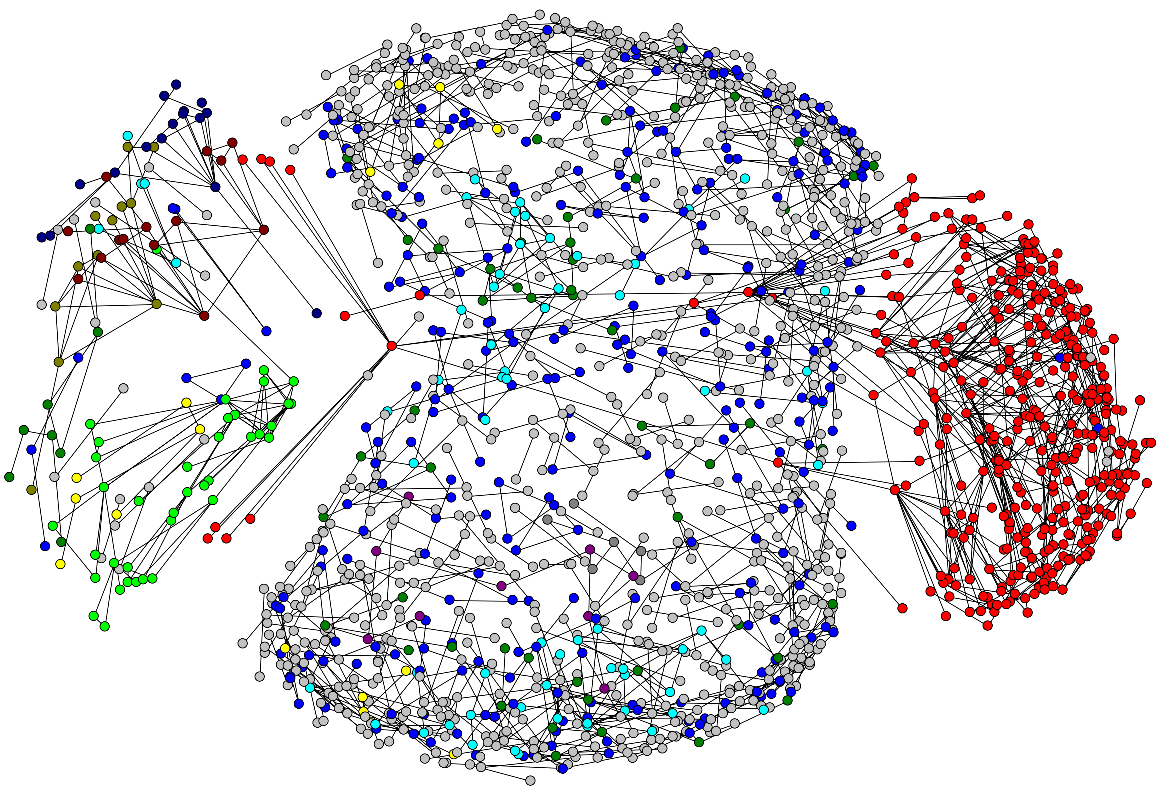
Figure 9: Global Technology Collaboration Network with and without IT firms, 1994-1996[15]



[15] Red indicates largest connected component.

Figure 10: Global Technology Collaboration Network with and without IT firms, 1996-1998[16]





[16] Red indicates largest connected component.

Figure 11: Indicators of the Tech Sector Bubble and Crash

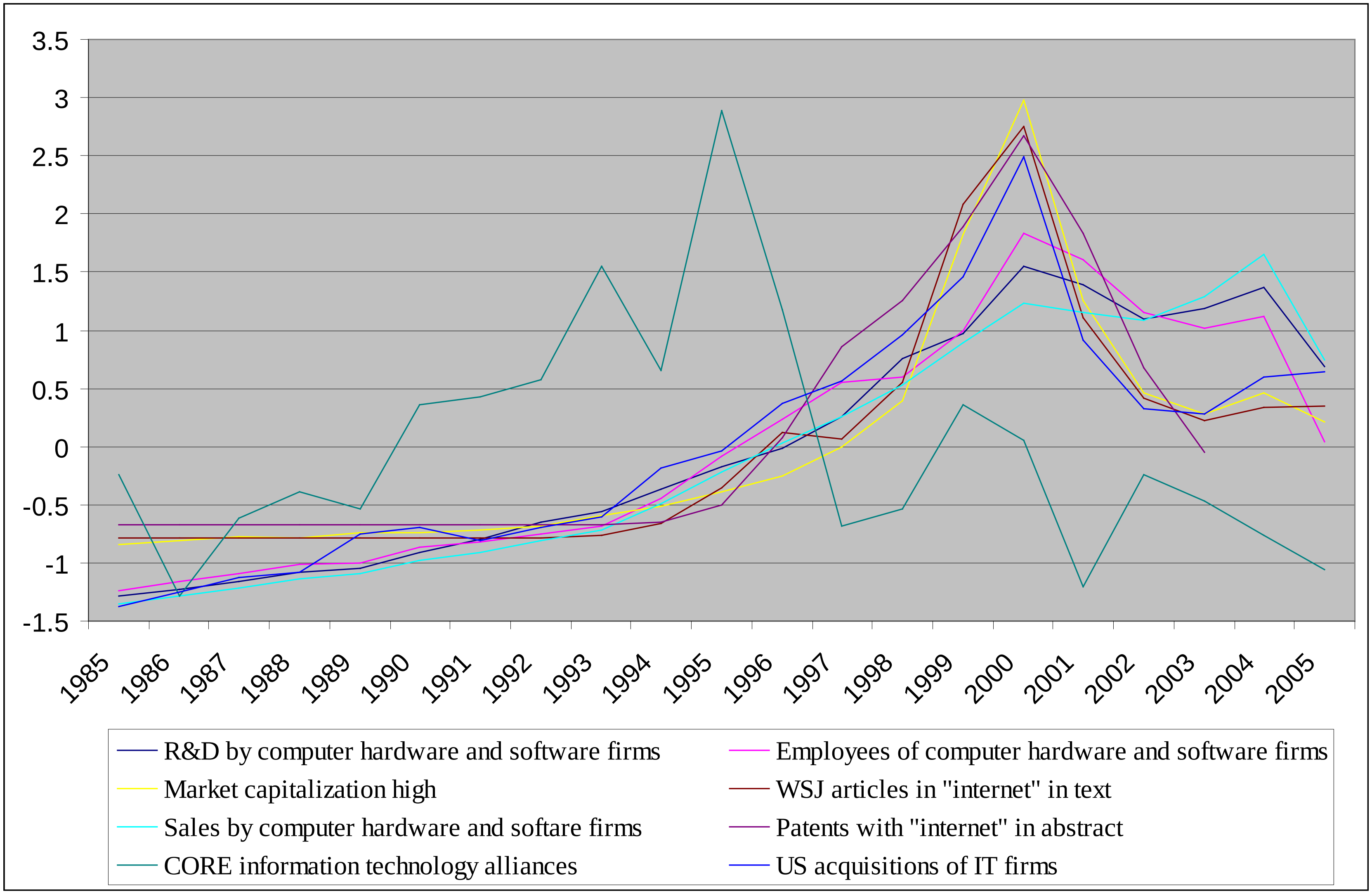


Table 1: Structural Properties of the Global Technology-Intensive Collaboration Network

Time Window	Number of participants in network	Average number of agreements per participant ("degree")	Density	Main Component		
				Number of participants	Percent of participants	Degree of participants
1990-1992	3232	2.51	0.0008	1857	57%	3.43
1991-1993	4638	2.69	0.0006	2627	57%	3.74
1992-1994	6033	2.88	0.0005	3516	58%	3.99
1993-1995	6911	2.7	0.0004	3856	56%	3.78
1994-1996	5995	2.53	0.0004	3036	51%	3.65
1995-1997	4636	2.15	0.0005	1850	40%	3.25
1996-1998	3013	1.98	0.0007	1046	35%	3.29
1997-1999	2691	1.72	0.0006	787	29%	2.73
1998-2000	2154	1.55	0.0007	234	11%	2.76
1999-2001	1746	1.52	0.0009	152	9%	2.92
2000-2002	1628	1.49	0.0009	124	8%	2.92
2001-2003	1397	1.4	0.001	169	12%	2.38
2002-2004	1285	1.32	0.001	86	7%	2.09
2003-2005	1809	1.32	0.0007	166	9%	2.17
Average	3369	1.98	0.0006	1393	31%	3.08

Table 2: Descriptive Statistics and Correlations

All Industries	**Mean**	**SD**	**N**	**1**	**2**	**3**
1. Number of alliances	28.81	102.39	1280			
2. Scope of alliances	4.76	2.41	288	-.04		
3. Percent IT alliances	.19	.30	1280	.26**	.09	
4. Technological change index	.00	1.67	1280	.16**	.19**	.10**
Non IT Industries						
1. Number of alliances	16.48	62.34	1216			
2. Scope of alliances	4.83	2.64	224	.03		
3. Percent IT alliances	.16	.27	1216	.03	.26**	
4. Technological change index	.00	1.67	1216	.13**	.24**	.11**
IT Industries						
1. Number of alliances	262.98	281.50	64			
2. Scope of alliances	4.50	1.29	64	.09		
3. Percent IT alliances	.74	.11	64	.29**	-.67**	
4. Technological change index	.00	1.68	64	.61**	-.08	.24

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 3: Fixed Effect Panel Regressions

	Alliance Scope		Percent IT Alliances	
	Rest.	Full	Rest.	Full
All Industries				
Constant	3.63**	3.63**	.00	.00
	(.47)	(.46)	(.06)	(.06)
Industry controls	[a]	[a]	[a]	[a]
Technological change index		.28**		.02**
		(.06)		(.00)
Adj. R squared	.39	.43	.34	.35
F of change		18.89**		18.37**
N	287.00	287.00	1279.00	1279.00
Non IT Industries				
Constant	3.27**	3.27**	.00	.00
	(.51)	(.49)	(.06)	(.06)
Industry controls	[a]	[a]	[a]	[a]
Technological change index		.38**		.02**
		(.08)		(.00)
Adj. R squared	.39	.45	.19	.20
F of change		22.92**		16.91**
N	223.00	223.00	1215.00	1215.00
IT Industries				
Constant	5.83**	5.83**	.69**	.69**
	(.26)	(.26)	(.03)	(.03)
Industry controls	[a]	[a]	[a]	[a]
Technological change index		-.06		.02*
		(.08)		(.01)
Adj. R squared	.38	.37	.06	.10
F of change		.58		4.10*
N	63.00	63.00	63.00	63.00

* p<.05; **p<.01

[a] Coefficients for industries omitted to preserve space