The Emergence of a Small World in a Network of Research Joint Ventures

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Abstract: Using the CATI Database of cooperative research and development (R&D) agreements, this paper applies methods from social network theory to study emergence of networks of firms cooperating in research joint ventures (RJVs) during the Twentieth Century. In this paper, a cooperative agreement between firms is modeled as a connecting link in a network, where the nodes of this network represent participating firms. The resulting R&D network is emergent in the sense that individual RJVs are sub-components of a larger network in which many of these RJVs are inter-linked by virtue of the presence of hub firms. This paper shows that the largest growth in the R&D networks occurred during the last three decades of the Twentieth Century, with the largest increase in the R&D collaboration occurring in the chemicals, telecom and modern materials/technology sectors. Based on our analysis of the data, during this period we find that the emergent R&D network has a pattern of collaboration (degree distribution), in which there are a large number of firms with at most one link and small number firms that have a large number of links. Over the same time period our analysis shows that, while statistics such as the clustering component and degree ratio are becoming smaller, the diameter of the network is also decreasing. This indicate that although the network is becoming sparser and more locally clustered, individual firms within this network are closer to each other in terms of the average number of links separating them from other firms. This is due to the presence of highly connected hub firms, which are linked into and collaborating across multiple research joint ventures. It is the presence of these R&D hubs that lead to the emergence of the small world in our emergent R&D network.

Key Words: Research and Development (R&D); Research Joint Ventures (RJVs); R&D Networks; Small Worlds; Social Network Analysis.

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1 Introduction

The objective of this paper is to characterize the pattern of evolution for network alliance between firms participating in research joint ventures. From this perspective, this paper carries two main goals. Firstly, we want to observe the number of firms that started cooperating in research joint ventures (RJVs) and how this number has changed over time. Also, we want to see how the number of firms participating in RJVs within each technological class has changed over time. Secondly, we want to characterize differences that emerge in the topology of these networks as they mature overtime. The purpose of doing this is that different network topologies have different stability properties. They also have different properties in terms of the relative efficiency (i.e. in terms of the Pareto gain for RJV members) and in the rate and accuracy of information diffusion throughout the network. These properties of different topologies will also depend on the relative size of the network. Hence, certain topologies will perform better at different stages of the research joint venture life cycle.

In order to do this, we use the Cooperative Agreements and Technology Indicators (CATI) Database developed by John Hagedoorn and Marc van Ekert at the University of Mastrich (Hagedorn and van Ekert, 2002). This data set, which extends from 1887 to 2006, covers cooperative agreements between firms and spans both domestic and international agreements. We focus only on those agreements that can be characterized as research joint ventures, as this will be the focus of our study. Our analysis begins in 1899 rather than 1887, because this is the year when the first RJV agreement is recorded in the CATI dataset. The decision was made to end our study in 2000 rather than 2006, so that our study could focus on decade-by-decade transitions in the R&D network during the Twentieth Century. We divide the data set into the following six epochs: 1899-1944, 1945-1959, 1960-1969, 1970-1979, 1980-1989, and 1990-2000. We also group participating firms by industry, in order to identify industry specific collaborations. The decision was made to focus only on research joint ventures because we are interested in how our empirical study in this paper supports and informs the theoretical model developed in Goyal and Moraga-Gonzalez (2001).

The model contained in Goyal and Moraga-Gonzalez (2001) extends the framework for studying research joint ventures that was developed in papers by D'Aspremont and Jacquemien (1988, 1990) and Kamien, Muller and Zang (1992). Other important papers in this literature include Spence (1984), Katz (1986), De Bondt (1997), Leahy and Neary (1997), Petit and Tolwinski (1999) and Suzumura (1992), to name but a few papers from this vast literature. These papers collectively study the beneficial role that cooperative R&D agreements (in particular RJVs and Research Cartels) have on internalizing information externalities that occur as a consequence of the innovation process occurring within individual firms. In these papers, the information externality is modeled as a positive spillover that can be freely appropriated by other firms. This leads to a disincentive on the part of individual firms to invest in R&D, which can be removed when firms either jointly invest in R&D or establish an agreement for sharing knowledge acquired from research.

One of the underlying issues with the cooperative R&D model is that spillover parameter is somewhat of a "black box". Furthermore, in the most basic of these models, information transfers have been assumed to be bi-directional and as a consequence the benefits from R&D in equilibrium emerge as being symmetric across firms. Although subsequent generalizations of this model have remedied this problem (e.g. Kamien and Zang (2000), Salant and Schaeffer (1998, 1999)), these models are usually quite small with respect to the number of competing firms. This is not altogether an unreasonable assumption from the perspective of model tractability and given the model's oligopolistic setting. However, Goyal and Moraga-Gonzales (2001) were able to extend the basic model of cooperative R&D so that RJVs could be modeled as a network. In doing this they were able to incorporate and allow for richer cooperative structures in this model. Prior to their paper, firms were usually modeled as existing either inside or outside a RJV agreement (one exception being Kamien and Zang (1993), where two RJVs compete). Under the framework of Goyal and Moraga-Gonzales (2001) firms can now be members of multiple RJVs. As a consequence the process of R&D spillover and knowledge diffusion can now be understood as a consequence of the emergent formation network of a network of overlaying research alliances.

It is this aspect that we seek to model with the CATI dataset. Using the statistics tools from social network theory, we are able to characterize the emergent network structure of R&D cooperation between firms and how the topology of this R&D network evolves over time. We find that there is a common pattern in place for this R&D networks that occurs across the time period studied in this paper. Across all periods, it was found that the R&D network was not complete, in the sense that there are always at least two firms between which an broken path of links cannot be found. Furthermore there is no symmetry in number of connections that each firm in the network had with other firms. Most of the firms in the R&D networks were of degree one, i.e. most firms were engaging in an RJV exclusively with one other firm. However, at the same time there are some firms that had a very large number of connections with other firms, e.g. in the period between 1990-2000, Mitsubishi, Mitsui and Philips participated in the largest number of research collaborations, partnering with 56, 67 and 91 firms respectively.

However, in general, for the majority of firms the number of connections with other firms seldom exceeded three in number, with the degree distribution being characterized by a power law property. What this says is that the R&D networks modeled in our dataset were emergent, occurring as a consequence of firms forming small bi-lateral alliances with other firms, rather occurring as a consequence of design. As would be the case if the network were fully connected, which would imply a research joint venture across all participating firms in an R&D network, or if the structure of the network had symmetry in the number of connections between firms. This type of degree structure typically characterizes star networks, where there is a single hub firm and other participating firms make up the periphery.

Overtime, it was noted that the density of the R&D networks declined, while the average degree of R&D network was increasing. This means that over time, size of the number of firms participating in these research networks increased significantly, compared to the number of alliance or links between these firms. Most significantly it was found that over the last three decades, the R&D networks are characterized as small world networks, pointing to a significant shift in the predominant topology of these networks. In all of these networks there is a giant component, which features this hub firm. It is well known that small world networks are extremely effective conduits of information. This indicates that, over time, the R&D network has evolved from a collection of small alliance dominated by hub firms, towards a larger network, where the predominant need is information transmission and diffusion. Furthermore, this pattern of collaboration, as described by the degree distribution of the R&D network, conforms to that of a scale-free network. These networks are known to have a high fault tolerance, in the sense that the random removal of firms from the R&D does not affect its overall function.

This paper is organized as follows: In the section two, we give a breakdown and explanation of the statistics tools from network theory and how they will be used in this paper. In section three we provide a description of the data set used in this study and a characterization of the aggregate data and the data by industrial sector in terms of their network structure. Section four provides a description and characterization of the pattern of network formation that emerges over time. Section five provides the conclusion and a discussion of future avenues of research.

2 Network Theory

This section provides an overview of network theory and some important descriptive statistics that will be useful in uncovering the properties of the R&D network described in this paper. The interested reader is encouraged to consult Jackson (2008) or Newman (2003) for more in depth coverage of this topic. A network will be defined as an undirected graph composed of a set of nodes N and links E, where the nodes are connected by these links. A network can be simply written as $G = (N,E)$. In this paper, the R&D network is modeled as an undirected graph, since cooperative agreements are defined as mutually to the parties engaging in the agreement. In the R&D network the set of nodes N represent firms and the set of links between firms E represent R&D partnerships formed as part of a RJV. A network G is a *connected network*, if a path can be traced between any two nodes in this network. A network is said to be a *star network* if there exists a node i in this network such that every link involves node i. If this is so, then node i is the *hub* (or center) of the star network. All other nodes are said to be in the *periphery*.

A network G is said to be *regular* if each node in this network has the same number of links, or more formally if $deg\ i\ = k$ for each node $i \in N$, where $deg\ i$ denotes the degree or number links originating from node i, then G is said to be regular. An R&D network is said to be *symmetric* if it is *regular*. The average degree of the network G is defined as $< deg >= 2m/n$, where n is the total number of nodes in the network and m is the total number of links. The density of a network G is a measure given by the following

$$D\ G\ = \frac{2m}{n(n-1)}$$

The density of a network keeps track of the relative fraction of links that are present in the network G, expressed as a ratio of the actual number of links out of the number of links that are possible. It is simply the average degree divided by $n - 1$.

The degree distribution of a network G is the relative frequency of nodes that have different degrees. That is, $P(d)$ is the fraction of nodes in G that have degree d or less. Note that if G is a regular network, where all nodes have k connections, then $P(k) = 1$ and zero for all other values of $d \neq k$. Beyond this degenerate distribution, the most common degree distribution associated with networks is the Poisson distribution, which is used when modeling Poisson random networks. A *random network* is a network in which any two nodes are linked with some probability. In a Poisson random network, it is the Poisson distribution that determines the probability of any two nodes being linked.

The other important distribution, which is well known in economics and the social sciences because of its association with the work of Pareto and Zipf on income distribution and linguistics, respectively, is the *scale-free distribution*

$$P(d) = cd^{-\gamma}$$

where $c > 0$ is a normalizing scalar and d denotes the degree. The interested reader should consult Mitzenmacher (2004) for a good overview of the literature on power laws, their history and application. A network is said to be scale-free if its degree distribution is characterized by the scale-free distribution Scale-free distributions have “fat tails”. This implies that if a networks is scale-free then there tends to be a large number of nodes with a very small number of links and few nodes with a large number of links, than if the links were formed independently so that the degree distribution were Poisson.

As shown in Albert et al. (2001), this has important implications for the error tolerance of these large network. If a network’s degree distribution is scale-free, then randomly deleting nodes as no impact on key characteristics that determine the functionality of the network. The reason is as follows: suppose the network’s degree distribution is given by the Pareto distribution. This would imply that less than 20% were connected with 80% of the network. Deleting 5% of the nodes at random would amount to deleting only 0.1% of these highly connected hub nodes. It was shown that to remove this fault tolerance from scale-free networks, these hub nodes had to be targeted exclusively. From the perspective of this study, the existence of a scale-free R&D networks would the persistence of collaborative R&D during periods of slow economic growth, when some firms may be forced to curtail or cut back on R&D expenditure.

For networks that are not fully connected the component structure is of interest. As there will generally be many sub-components that are identifiable, the size of these components is very important and there is a classifying convention for this. A component is said to be *small* if it has fewer than $n^{2/3}/2$ nodes and large if it has at least $n^{2/3}$ nodes. The *giant component* of a network refers to its largest component. Note, that this definition implies that the giant component of a network need not be large. The reason why the giant component is of interest in the study of networks, is that it permits a bound to be constructed with respect to the maximum number of nodes that might be reached when traversing a network from any node contained within it. From the perspective of the analysis conducted in this paper, this has implications for the diffusion of knowledge generated from R&D. This implies that firms within the giant component of any R&D network are more likely to benefit from knowledge spillovers that occur as a consequence of firms investing in R&D.

A set of all nodes that are directly linked to node *i* in a network *G* is the neighbor's set for that node:

$$N_i = \{j \in N; ij \in N\}$$

The second order neighbors for node *i* is the set of node *i*'s neighbors that are not directly linked to node *i*:

$$N_i^2 = \{k \in N_j; j \in N_i, k \notin N_i\}$$

The clustering coefficient of a node measures the probability that the neighbors of that node are also its neighbors. The clustering coefficient of a node *i* is given by

$$C_i = \frac{2|jk: j, k \in N_i, jk \in E|}{\deg i \ (\deg i - 1)}$$

Note that, if $\deg i = 0$ or $\deg i = 1$ $\deg(i) = 1$, then the clustering coefficient C_i is zero. This implies that if a firm is not participating in an RJV or if it is an RJV with one other firm, then it will be isolated and as such the clustering coefficient for that firm will be set to zero. The total clustering coefficient for the network *G* is the average of the clustering coefficients over all nodes in the network and is given as

$$C(G) = \frac{_{i \in N} C_i}{n}$$

where *n* is the total number of nodes in the network.

The distance d_{ij} between any two nodes in a network (geodesic) is the smallest path (number of links) between these two nodes. The average distance can be calculated by the following expression

$$AD\ \ G\ \ = \frac{{}_{i\neq j}\, d_{ij}}{n(n-1)}$$

Note that, if the two nodes i and j are not connected, then the distance between them is infinity ($d_{ij} = \infty$). The network diameter is the maximal shortest path between any two nodes in the network. In a disconnected network, the diameter is infinity. For this the average distance of the giant component is used as a proxy for the average of the network when it is not fully connected.

The term *small world* is used to embody the observation that many large networks tend to have small diameters, small average path lengths and are highly clustered. The small average path length and small diameter imply that it is relative easy to traverse the network in a small number steps. The high level of clustering implies that once a location has been reached there are many neighbors located nearby. In essence, this permits only a small degree of separation between any two entities existing in the network, facilitating and accelerating the relay and diffusion of information across the network.

This implies that for any network *G* to be defined as a small world network it must satisfy the following four conditions:

1. The size of the network, as expressed in terms of the total number of its nodes, is high compared with its average degree $< deg >$, i.e. average number of connections that each node has.
2. The network is cohesive so that its total clustering coefficient $C(G)$ is high.
3. A giant component of the network *G* exists and contains a large share of the population.
4. The average distance between nodes in the giant component is small, so that the average diameter $d(G)$ of the network *G* is of the order $\ln(n)$.

This definition of a small world network is based on Goyal et al. (2006), which is an extension of the definition provided in Watts (1999). The difference is the inclusion of network cohesiveness (Requirement 3), which requires that the majority of the networks nodes are contained within its giant component. Requirements 1, 2 and 4 correspond with the definition provided in Watts (1999) and emerge from a comparison between small world networks and random networks that was conducted in Watts and Strogatz (1998).

3 Descriptive Statistics

The data used in this study is from CATI (2002) database, which is a relational database ranging from 1887-2006 and contains over 15,000 cooperative agreements involving some 9,500 firms. The CATI database contains only those inter-firm agreements that pertain to some arrangement for mutual transfer of technology or joint research. They include agreements such as joint research pacts, joint development agreements, cross licensing, R&D contracts, research joint ventures and research corporations. The following minimal information was always available for every agreement: the names of the firms involved, the year of establishment, the type of cooperative agreement, fields of technology and an abstract of the alliance purpose. The following information was also contained within the database when available: involvement of banks, universities and/or governments, time horizon and year of break-up, the name of the agreement, the direction of technology and capital flows and the SIRD indicator. Given the long duration of the dataset, the decision was made to break the dataset into six epochs: 1899-1944, 1945-1959, 1960-1969, 1970-1979, 1980-1989, and 1990-2000. As stated in the introduction, our analysis begins in 1899 rather than 1887, because this is the year when the first RJV agreement is recorded in the CATI dataset. The decision was made to end our study in 2000 rather than 2006, so that our study could focus on decade-by-decade transitions in the R&D network during the Twentieth Century.

Within each epoch, the dataset is grouped technological class and by the country in which the R&D agreement occurred. The following technology classes are used in this study: chemicals, telecommunications, aircraft, automotive, defense, food and beverage, space technology, mineral exploration, drilling and mining, consumer electronics and instrumentation heavy electrical equipment and engineering advanced materials; biotechnology, medical technology and nutrition and automation, computers and information technology. The sub-groupings within biotechnology include pharmaceuticals, nutrition, fine chemicals, agro-biotechnology and environmental sciences. Within advance materials the sub-groupings include technical ceramics, technical plastics, powder metallic, fiber composites, electromagnetics and optics and metal alloys. The automation, computers and information technology sector includes computer hardware, industrial automation, microelectronics, and computer software.

The R&D network is constructed using incidence matrices. An incidence matrix is a square matrix with elements that are either 0 or 1. Each row and column corresponds to a node in the network. If an element of the incidence matrix is 0, then this implies that there is no connection between two nodes. If the matrix element is 1, then the two nodes are connected to each other. Our data set specifies, in each time period, a list of RJVs giving the names of the names of the firms involved. The dataset also provides technology field in which the RJV occurs. As such, incidence matrices are formed for all firms in each time period, as well as for each technology class. Each incidence matrix is formulated by allocating each firm a row and column vector. Then depending on whether or not firms are collaborating, an incidence matrix is constructed by inserting either 1 or 0 into the appropriate matrix cell. In this way an R&D network is constructed for each technological class and for the entire dataset in each time period. The analysis for each network is performed using network statistics that were coded in in MATLAB.

3.1 Aggregate Descriptive Statistics

Our analysis of R&D collaboration starts with an examination of the number of firms engaged in RJV agreements over time. Table 1 tells us that the number of firms engaged in RJV agreements has grown substantially from 33 firms in the period 1899-1944 to 2,348 firms in the period 1990-2000. The pattern of growth is interesting in the sense that Table 1 shows that the numbers of firms engaged in RJVs doubled in the periods 1899-1944 and 1946-1959; 1960-1969 and 1970-1979; and 1980-1989 and 1990-2000. However, between the periods 1946-1959 and 1960-1969 and 1970-1979 and 1980-1989 there was an exponential growth in the number of RJV agreements. These periods of substantial growth in the number of participating firms coincided with decades in which there was substantial growth in the world economy. It is significant that even in periods where economic growth was slower that there is a consistent “doubling” pattern to these agreements. This points to the importance of RJVs as a means of sustaining R&D and offsetting its risks over substantial time periods and indicates the important role that RJVs have had in the substantial growth in R&D that was reported during the Twentieth Century.

Given that we have established that there was a substantial growth in the overall size of the R&D network, as expressed in terms of an increase in the number of its nodes, what can we now say about the pattern of connections within the network? Table 1 shows that there was a substantial increase in size of the giant component of the R&D network from 10 firms in 1899-1944 to 1,402 firms in 1990-2000. As a percentage of the network the giant component grew from 30.3% in 1899-1944 to 60% in 1990-2000. In comparison to the dramatic and substantial growth in size of the giant component, the second largest component has almost remained stationary in size, ranging between 7-10 firms in the period from 1945-2000. In terms of the number of firms engaging in bi-lateral agreements, there has been an overall increase from 16 firms in 1899-1944, constituting 48.5% of participating firms in RJVs, to 1,322 firms in 1990-2000, constituting 56.3% of firms involved in RJVs.

At the same time, Table 1 shows that there was an increase in the number of star networks during the periods under our study. The number star networks was three in the 1899-1944, subsequently rising to 14 between 1945-1959. In the period 1960-1969, the number of star networks increased to 27. The growth of the star networks was significant in the last three decades from 89, to 233 and 312 respectively. A similar pattern of growth can be found in the giant component of the R&D network; this can be seen in Table 1, which shows that from 1945 onwards, the majority of these star networks were positioned within the giant component of the R&D network. Table 4 shows that complete networks of size greater than or equal to 3 are relatively small in number by comparison to star networks. The reason for this is that these complete networks are in fact multi-firm RJVs, composed of three of more firms. One explanation for the small number of these large RJV agreements is that they are quite unstable, requiring large efforts to coordinate. However, it is interesting that during the 1880's and 1990's, the prevalence of these agreements rose and their size rose also dramatically. One explanation is the period of high growth experienced by the world economy during this decade.

It is important to note that the bi-lateral RJV agreements are not necessarily islands of R&D cooperation existing in isolation from the giant component of the R&D network. This is something that is indicated by the low number of network components that are observed across all time periods in the data set. In fact, the majority of the largest star networks are composed of RJV agreements between the hub firm and one other firm, within its periphery. This pattern of collaboration is shown in the network diagrams given in Figures 1-4. These diagrams depict star networks for some of the most highly connected hub firms. One can note that the majority of firms in these networks are in bi-lateral RJVs with the hub firm. Table 7 provides clustering coefficients for the leading hubs. The clustering coefficient for each firm, provides the proportion of a firm's collaborators, which also have collaborators that are collaborating that firm. Shell in the 1970's can be seen to have a very high clustering coefficient of 0.219 when compared to 0.0615 Mitsui during the same time period. The size of the star networks the star networks is similar, with 22 firms for Mitsui's star network and 21 firms for Shell. The difference can be seen in the number of triads that are formed by second order neighbors also being linked to the hub. As a consequence the circumference of Shell's star network is more connected than Mitsui's star network.

Furthermore, a significant proportion of these star networks were inter-linked. By the 1970's, when the small world property begins to take hold in the network, at least 50% of star networks are linked with other star networks. This statistics remains consistent from this point onwards. It is also worthwhile noting that the number of connected hubs is also growing over time. In the time period 1899-1944, the number of hub firms linked to other star networks was equal to 1. Implying that there was a single hub firm connecting the two star networks. By 1945-1959, there were 10 inter-linked star networks sharing 7 hub firms, implying that at least some of these star networks shared hub firms. Over time, the proportion of shared hubs to linked star networks has risen, implying that many of these linked star networks share multiple firms. This is attested by the size of the second order neighborhood for hub firms such as Mitsubishi and Mitsui in the last two decades of our data set; Table 7 shows that their first and second order neighbors collectively constitute the majority of the giant component in which both firms are situated. This points to a high degree of overlap in RJVs.

Table 1 shows that the clustering component and density of both R&D network and its giant component have fallen over time. While the clustering component measures cliquishness, the density provides a measure of sparseness of the network. This indicates that the R&D network and its giant component have become sparser, but less cliquish, over time. This does not mean that the R&D is less connected. Rather, over time, the majority of the R&D network have become constituent members of its giant component and therefore are higher order neighbors of the majority of firms in the R&D network. What has happened is that, while the R&D network and its giant component have grown substantially, the diameter of the R&D network, as characterized by the mean distance of the network giant component has remained, relatively stationary. What this indicates is that although the size of the R&D network and its giant component have increased substantially in last two decades of the Twentieth Century, the distance between individual firms within this network, as measured in terms of the average number of links separating it from other firms, has not changed substantially.

The idea that a network that is sparse in structure, with a very large number of disperate and locally clustered nodes, can still be relatively small in size in terms of the number of links it takes to traverse shortest path across its diameter, is the essential feature that characterizes a small world. In terms of R&D this has an important implication with respect to the rate of information diffusion, in the sense that across all industries there is on average at most three degrees of separation between any two firms in the giant component of the network. In Section 4 of this paper, we will show that this is the reason why the diameter of the R&D network has remained stationary in the last two decades. We will show that he hub firms of the star networks play an important role in this, functioning as connectors, shortening the distance between firms in the giant component of the R&D network. We also show that these firms play an important role in facilitating the robustness of the R&D network with respect to firms leaving RJV partnerships.

3.2 Descriptive Statistics by Sector

This section reports network statistics for each of the technological sectors contained within the CATI dataset. Table 1 shows that initially there were 7 industrial sectors in which collaborative research was occurring between 1899-1944. This number later rose to 8 sectors in 1945-1959 and 12 sectors from 1960 onwards. The breakdown of each sector in terms of its collaborative R&D network is contained in Table 2. This table focuses on RJV collaboration in six industrial sectors: chemicals, consumer electronics, mining and mineral exploration, advanced materials, telecommunications and biotechnology. The network statistics for the other six industrial are provided in the Appendix to this paper. Of the sectors provided in this table, only biotechnology, space, aircraft, defense and food and beverage are not represented in every time period.

We note that while overall there was significant growth of firms participating within RJVs during the last century, the growth of RJVs in the chemical sector, when taken as a proportion of the total number of RJVs, actually decreased over time. In the period 1899-1944, there were seven participating firms engaging in RJVs (19% of firms in the R&D network); with all firms based in either the USA or Germany. Between 1945-1959 this rose to 21 firms (29%) participating in RJVs. In the next two periods (1960-1969 and 1970-1979), although the number of firms that were collaborating in RJVs in the chemicals sector rose to 61 and 187 firms respectively, the number of firms as a proportion of total firms participating in RJVs remained nearly stationary at 21% and 25%. In the last two time periods (1980-1989 and 1990-2000), the number of firms in the chemicals sector increased dramatically, to 378 and

498 firms respectively, but the proportion of participating firms in this sector decreased to 18% and 17%.

A similar pattern can also be seen to be occurring within the mining and minerals exploration sector, where in 1899-1944 the majority of RJVs were in mining and minerals exploration. The most connected firms, Southern Oil New Jersey and Texaco, were also contained within this industry during this time period. However, in the period 1945-1959 the number of participants in RJV agreements had fallen to 4 firms. Although this subsequently rose, the number of participating firms never exceeds 20% of the overall data set during any other time period during the last half of the Twentieth Century. The greatest growth in the number of RJVs was experienced in occurred in technological classes and in times that preceded substantial technological change. Examples are the dramatic growth RJV participation in the information technology and consumer electronics sectors in the 1980's and the growth in RJV participation in telecommunications during the 1990's.

Perhaps the most interesting difference between these sectoral R&D networks and the overall R&D network is in the density statistic, which measures the number connections in the network as a proportion of the number of potential connections. Most technological sectors have R&D networks that are sparse. The major exceptions are industries such space, aircraft and food and beverage. However, this is more indicative of the small size of these networks, when compared to other industries.

4 Dynamic Properties of the R&D Network

As explained in section two there are four conditions that an R&D network must satisfy for it to have the characteristics of a small world. The first of these conditions is that the average degree of the R&D network (i.e. the average number of collaborators that firms have in the network) is small in size when compared to the total number of collaborating firms. We note from Table 1 that while the number of firms has risen dramatically over time, the mean number of collaborators working with each firm has stayed relatively stationary at between 2-3 firms. This trend also appears in all of the technological classes contained in our data set, as can be seen from Table 2. In general this implies networks are sparse, in the sense that number of links are less than the number of firms in the network, but sufficiently dense to permit a variety of sub-structures within the R&D network, as characterized by the degree size being greater than one.

Two comparisons will be of interest. The first will be a comparison between random networks and the R&D network. Random networks share many features with small world networks, in the sense that both networks are very sparse with small densities and have similar degree structures. However, small world networks are more clustered than random networks, with higher clustering coefficients, and they also have a smaller network diameter. The other prerequisite is that size of the must also be large relative to the average degree the network. Without this the network will be too small.

The other important characteristic that we will discuss is this section is the role played by the star networks and their hub firms. We have already indicated that a large proportion of the R&D network and its giant component are composed of star networks and many of these star networks are interconnected with other star networks. We will show that these firms play an important role in maintaining the R&D network's topological structure, to the extent that when the top 5% of these hub firms are systematically removed from the network, the giant component of the network shrinks in size. Furthermore, this does not happen when firms are deleted randomly and the small world properties persist in this network. This has important implications for the role of these hub firms in facilitating the robustness of the R&D network to systemic shocks, such as recessions when firms will exit the R&D network.

4. 1 Emergence of the Small World Property

It is only in the last three decades of the Twentieth Century that the R&D network begins to have small world properties. Prior to this time the number of firms in the R&D network is too large in size and the density of the R&D network is too high. Indicating that the network is too dense in terms of the number of connections relative to number of its nodes. From the 1970's this begins to change and the density begins to be similar to that of random networks with a similar number of nodes. The main difference between the R&D network and the random network is in terms of its clustering coefficient and diameter. These are far larger than in the random network. Indicating that although the network is sparse in terms of number of connections between firms, it is more locally clustered and firms are closer together. The predominant reason for this, as we will argue in the next section, is the existence of hub firms and the star networks within the giant component of the R&D network and the high degree of interconnectedness between these hub firms.

4. 2 Star Networks, Hub Firms and Network Robustness

The star networks have the greatest role to play in terms of the emergence of the small world property in these networks. The star network consists of at least one hub firm, with which the majority of firms hold a bi-lateral RJV agreement. Table 4 shows that the number of these star networks rose dramatically over time, from 3 star networks initially in 1899-1944 to 312 star networks by 1990-2000. Table 1 shows that from 1945 onwards, the majority of these star networks were positioned within the giant component of the R&D network. Furthermore, a significant proportion of these star networks were inter-linked. By the 1970's, when the small world property begins to take hold in the network, at least 50% of star networks are linked with other star networks. This statistics remains consistent from this point onwards. It is also worthwhile noting that the number of connected hubs is also growing over time. In the time period 1899-1944, the number of hub firms linked to other star networks was equal to 1. Implying that there was a single hub firm connecting the two star networks. By 1945-1959, there were 10 inter-linked star networks sharing 7 hub firms, implying that at least some of these star networks shared hub firms. Over time the proportion of shared hubs to linked star networks has risen, implying that these linked star networks share multiple firms.

In order to investigate the role that these stars networks in the R&D network, we begin by randomly deleting 5% of the cooperating firms. Table 6 shows that when this is done we note that there is a small increase in the average distance in the giant component across all time periods. However, the impact on the clustering coefficient is not very large. However, deleting 5% of the most linked firms leads to dramatic changes in the network structure. First, the size of the giant component drops, and in the last three periods; it decreases in size by between 21 - 25% from the original size of giant component. Also, as would be expected, the average distance between firms rises in the last three periods. However, there is also no significant change in the clustering coefficient. This indicates an importance between the emergent structure of R&D networks and that of the informal academic research networks that were reported in Goyal et al. (2006). By comparison, they report an increase in the size of the clustering coefficient. This indicates that the star networks play the role of connectors, sharply reduce distance between firms engaging in research. Hence, it is expected that the clustering coefficient will increase if some of the most connected firms are deleted because of declining of the size of the network. However, we find the clustering coefficient decreases, particularly in the last three decades. This indicates that on average the individual clustering coefficient of firms linking to the highest degree firms decreased when highly connected firms are deleted. One reason for this is that there are multiple hubs cross-linking between star networks. As such the R&D network is more robust to the removal of the larger hub firms, with less connected hubs remaining to fulfill this role. As such distance increases, while clustering remains relatively high.

Table 7 provides descriptive network statistics for the most connected hub firms in the network. Since the 1980's Mitsubishi, Mitsui and Phillips have been the most prolific collaborators, with these three firms being top three participants in RJVs. Overall Mitsubishi and Dow have consistently been among the top eight collaborating firm since 1945. The other interesting statistic is the growth in the overall size of second order neighbors for all of these leading hub firms during the 1980's and 1990's. This indicates that although firm's such as Mitsubishi, Mitsui and Phillips have a large number of direct collaborative links, this is a small fraction (and decreasing fraction) of the number of firms not directly connected to a hub, but connected to one of its neighbors. It is worth noting that in the period 1990-2000, Mitsubishi had 437 firms as second order neighbors and there were 91 firms with which Mitsubishi was collaborating directly. This implies that within the giant component of the network, of which Mitsubishi was a member, 528 firms out of 1,402 firms were either collaborating directly with Mitsubishi or with one of its RJV partners. Similar proportions can be calculated for Mitsui and Phillips (as well as for other firms among this group) and would indicate the advantage that these leading hub firms have from the perspective of knowledge acquisition in this R&D network.

Table 6 shows the impact of deleting 5% of the firms from the network by choosing these firms at random. Overall there is very little impact on the network statistics when the two networks are compared. Furthermore, in the 1980's and 1990's when the network shows small world properties, deleting firms randomly has no impact on the existence of the small world. However, if instead 5% of the most connected firms are removed from the network, the impact is quite dramatic in terms of the reduction in size of the giant component. The most dramatic change occurs in the 1980's and 1990's, when there is a dramatic increase in the network diameter and a decline in the clustering coefficient. What this indicates is that the small world properties are disappearing when the most connected firms are removed from the network. Overall this indicates that without these hub firms and the star networks, the small world begins to break down. The effects are even more pronounced in earlier before the appearance of the small world. The only exception being the 1960's, when the most connected firm is Mitsubishi, which is not a member of the giant component in this decade and as such when removed has no significant impact on changing either the diameter or clustering coefficient of the network.

5 Conclusion

This paper provided a characterization of the structure of the R&D cooperation thru RJVs and its dynamic properties, as they emerged over the Twentieth Century. Using the CATI dataset we constructed an R&D network in order to identify the emergent properties of RJV collaboration. Our results firstly confirm the growing popularity of this type of cooperative R&D agreement during the Twentieth Century. However, our most significant results pertain the existence of a small world among firms collaborating in RJVs. This has important implications in terms of the rate of diffusion of information across the network as it implies that firms, which are relatively distant neighbors of each other, are in fact quite close to each other in the sense they share collaborators. We also showed that during the time period in question from 1970-2000, the R&D network's degree distribution exhibited scale-free properties.

This implied that there were a small proportion of highly connected hub firms contained with the R&D network, which were linked to the majority of firms in the R&D network. Firms such as Mitsubishi, Mitsui, Sumitomo, Phillips, Shell, VEBA and Dow feature among the top 5% of hub firms in most periods. One implication of this is that these firms have the opportunity to acquire more knowledge from their RJV partnerships than most other firms and thereby benefiting more from information spillovers than less connected firms. However we also show that these hub firms have an important characteristic in that without their presence in the network, its cohesiveness and small world property disappears. This points to the important role that these hub firms have in transmitting and disseminating knowledge in this network

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References

Albert, R.,. Jeong, H., Barabasi, A.-L., 1999. Diameter of the World-Wide Web. *Nature* 401,130–131.

Albert, R., Hawoong J., and Barabasi, A-L., 2000. Error and Attack Tolerance of Complex Networks. *Nature* 406, 378–82.

D'Aspremont, C., Jacquemin, A., 1988. Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review* 78, 1133–1137

D'Aspremont, C., Jacquemin, A., 1990. Erratum. *American Economic Review* 80, 641–642.

DeBondt, R., 1997. Spillovers and innovative activities. *International Journal of Industrial Organisation* 15, 1–29.

Faloutsos, M., Faloutsos, P. , Faloutsos, C., 1999. On power-law relationships of the internet topology, ACM SIGCOMM'99. *Computer Communication Review* 29, 251-263.

Goyal, S., Moraga-Gonzales, J. L., 2001. R&D Networks. *Rand Journal of Economics* 32, 686-707.

Goyal, S., van der Leij, M., Moraga-Gonzales, J. L., 2006. Economics: An Emerging Small World. *Journal of Political Economy* 114 (2), 403-412.

Huberman, B. A., Adamic, L. A., 1999. Growth dynamics of the World-Wide Web. *Nature* 401, 131.

Jackson, M., 2008. *Social and Economic Networks.* Princeton, NJ: Princeton University Press

Kamien, M., Muller, E., Zang, I., 1992. Research joint ventures and R&D cartels. *American Economic Review* 82, 1293–1306.

Kamien, M., Zang, I., 1993. Competing Research Joint Ventures, *Journal of Economics & Management Strategy* 2, 23-40.

Kamien, M., Zang, I., 2000. Meet me halfway: Research Joint Ventures and Absorptive Capacity. *International Journal of Industrial Organization* 18, 995-1012.

Katz, M., 1986. An analysis of cooperative research and development. *Rand Journal of Economics* 17, 527 – 543.

Leahy, D., Neary, P., 1997. Public policy towards R&D in oligopolistic industries. *American Economic Review* 87, 642–662

Mitzenmacher, M. 2004. *A Breif Histroy of Generative Models for Power Law and Log Normal Distributions.* At http://www.eccs.harvard.edu/~michaelm/ListByYear.html

Moody, J., 2004. The Structure of a Social Science Collaboration Network: Disciplinary Cohesion from 1963 to 1999. *American Sociological Review* 69, 213–238.

Newman, M., 2001. The Structure of Scientific Collaboration Networks. *Proceedings. Natural Academy of Sciences* 98, 404–409.

Newman, M., 2003. The Structure and Function of Complex Networks. *SIAM Review 45*, 167-256.

Petit, M.L., Tolwinski, B, 1999. R&D Cooperation or Competition? *European Economic Review* 43, 185-208.

Spence, M., 1984. Cost reduction, competition and industry performance. *Econometrica 52*, 101-121.

Salant, S., Shaffer, G., 1998. Optimal asymmetric strategies in research joint ventures. *International Journal of Industrial Organization* 16, 195–208.

Salant, S., Shaffer, G., 1999. Unequal treatment of identical agents in Cournot equilibrium. *American Economic Review* 89, 585–604.

Spence, M., 1984. Cost reduction, competition, and industry performance. *Econometrica* 52, 101–121.

Suzumura, K., 1992. Cooperative and non-cooperative R&D in an oligopoly with spillovers. *American Economic Review* 82, 1307–1320.

Watts, D. J., 1999. *Small Worlds: The Dynamics of Network Formation between Order and Randomness.* Princeton, NJ: Princeton University Press.

Watts, D. J., Strogatz, S., 1998. Collective Dynamics of 'Small World' Networks. *Nature 393*, 440-442.

Appendix: Tables and Figures

Table 1: Network Statistics for the R&D Network and its Giant Component

Period	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
Total firms	33	61	225	592	1602	2348
No. RJVs	16	39	120	517	1576	2724
No. Industrial Sectors	7	8	9	12	12	12
Tot. No. Links	46	62	264	686	2271	3090
No. Possible links	528	1830	25200	174936	1282401	2755378
Density	0.087	0.034	0.01	0.004	0.002	0.001
Number of comp'nts	10	14	50	92	213	378
Size of Giant	10	10	93	354	1,071	1,402
Size second Comp'nt	4	9	9	7	8	10
Av. Degree	2.788	2.033	2.347	2.318	2.835	2.632
Max Degree	8	6	14	31	85	91
Most Connected Firm	S.O./Tex	MBSHI	VEBA	MBSHI	MBSHI	MBSHI
No. Star Networks	3	14	27	89	233	312
No. Firms as Pairs	16	26	123	316	837	1,322
% Firms as Pairs	48.5%	42.6%	54.7%	53.4%	52.3%	56.3%
Clustering coefficient	0.409	0.271	0.246	0.197	0.196	0.191
Giant Component						
Mean Links	6	2	3.677	2.989	3.645	3.549
Max Links	8	4	14	31	85	91
Max Link Firm	S.O./Tex	BAY'R	VEBA	MBSHI	MBSHI	MBSHI
No. Star Networks	0	4	11	71	192	246
Mean Diameter	1.356	2.956	4.909	5.698	4.963	5.026
Max Diameter	3	7	13	16	14	14
Clustering Coeff	0.7615	0.15	0.38	0.22	0.239	0229
Density	0.667	0.222	0.4	0.009	0.003	0.0025

Table 2:Network Statistics for the R&D Network by Technological Class.

Periods	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
Chemicals						
Total Firms	7	21	61	187	378	498
No. of links	5	16	75	221	494	606
Average Degree	1.429	1.524	2.46	2.36	2.614	2.434
Cluster Coefficient	0.429	0.071	0.117	0.013	0.01	0.005
Density	0.238	0.076	0.041	0.102	0.147	0.157
Average Distance	1	2.956	2.52	4.48	4.109	4.141
Size of Giant	3	10	28	123	257	285
No. of Stars	0	5	4	28	58	67
Consumer Electronics						
Total Firms	7	10	20	45	109	122
No. of links	4	7	14	31	125	120
Average Degree	1.143	1.4	1.4	1.378	2.294	1.967
Cluster Coefficient	0	0.3	0.117	0.031	0.198	0.016
Density	0.19	0.156	0.074	0.104	0.021	0.193
Average Distance	1.333	1.333	1.333	1.93	3.665	4.274
Size of Giant	3	3	4	6	55	50
No. of Stars	1	1	4	7	14	17
Telecom						
Total Firms	5	2	6	27	184	227
No. of links	4	1	3	17	329	373
Average Degree	1.6	-	1	1.259	3.576	3.286
Cluster Coefficient	0.6	-	0	0.048	0.02	0.015
Density	0.4	-	0.2	0.086	0.338	0.314
Average Distance	1	-	1	1.33	4.868	4.545
Size of Giant	3	-	2	4	142	162
No. of Stars	0	-	0	3	21	23

Periods	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
New Materials Technology						
Total Firms	2	7	46	66	264	358
No. of links	1	5	29	43	239	313
Average Degree	-	1.429	1.261	1.303	1.811	1.749
Cluster Coefficient	-	0.429	0.203	0.02	0.01	0.005
Density	-	0.238	0.028	0.134	0.144	0.113
Average Distance	-	1	1.167	1.809	5.932	6.598
Size of Giant	-	3	4	7	102	158
No. of Stars	-	0	0	4	36	51
Information Technology						
Total Firms	2	11	52	156	525	732
No. of links	1	8	39	134	498	791
Average Degree	-	1.455	1.5	1.718	1.897	2.161
Cluster Coefficient	-	0.273	0.269	0.011	0.004	0.003
Density	-	0.146	0.029	0.229	0.142	0.178
Average Distance	-	1.333	2	2.89	5.273	4.877
Size of Giant	-	3	5	27	244	330
No. of Stars	-	2	3	13	69	95
Heavy Engineering						
Total Firms	2	12	25	69	165	195
No. of links	1	8	16	58	178	191
Average Degree	-	1.333	1.28	1.68	2.158	1.959
Cluster Coefficient	-	0.25	0.12	0.025	0.013	0.010
Density	-	0.121	0.053	0.207	0.314	0.274
Average Distance	-	1	1.667	2.652	4.199	4.047
Size of Giant	-	3	4	12	60	49
No. of Stars	-	1	4	8	11	17

Periods	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
Exploration and Mining						
Total Firms	11	4	50	59	60	61
No. of links	30	2	64	76	77	78
Average Degree	5.45	1	2.56	2.576	2.567	2.557
Cluster Coefficient	0.705		0.433	0.044	0.044	0.043
Density	0.546	0.33	0.052	0.395	0.386	0.441
Average Distance	1.19	1	1.429	2.54	2.974	2.429
Size of Giant	9	2	8	17	20	15
No. of Stars	0	0	2	2	2	2
Biotechnology						
Total Firms	-	-	-	56	234	456
No. of links	-	-	-	38	236	396
Average Degree	-	-	-	1.357	2.017	1.737
Cluster Coefficient	-	-	-	0.025	0.009	0.004
Density	-	-	-	0.185	0.225	0.156
Average Distance	-	-	-	1.6	2.058	4.048
Size of Giant	-	-	-	5	20	27
No. of Stars	-	-	-	2	34	62
Aircraft						
Total Firms	-	6	16	23	31	89
No. of links	-	15	27	32	44	116
Average Degree	-	5	0.225	2.783	2.839	2.729
Cluster Coefficient	-	1	0.842	0.127	0.095	0.033
Density	-	1	3.375	0.615	0.492	0.394
Average Distance	-	1	1.191	1.321	1.821	2.971
Size of Giant	-	6	7	8	8	19
No. of Stars	-	0	0	0	1	4

Periods	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
Food & Beverage						
Total Firms	-	-	8	41	79	103
No. of links	-	-	4	31	54	68
Average Degree	-	-	1	1.51	1.367	1.32
Cluster Coefficient	-	-	0	0.038	0.018	0.013
Density	-	-	0.143	0.232	0.149	0.115
Average Distance	-	-	1	2.191	2.214	2.214
Size of Giant	-	-	2	7	8	8
No. of Stars	-	-	0	4	6	9
Defence						
Total Firms	-	-	-	14	31	76
No. of links	-	-	-	11	33	81
Average Degree	-	-	-	1.57	2.219	2.132
Cluster Coefficient	-	-	-	0.121	0.071	0.028
Density	-	-	-	0.381	0.425	0.276
Average Distance	-	-	-	1.333	1.381	3.638
Size of Giant	-	-	-	4	7	36
No. of Stars	-	-	-	1	2	7
Space Technology						
Total Firms	-	-	-	14	29	52
No. of links	-	-	-	11	26	53
Average Degree	-	-	-	1.57	1.793	2.039
Cluster Coefficient	-	-	-	0.121	0.064	0.040
Density	-	-	-	0.381	0.506	0.442
Average Distance	-	-	-	1.333	1.333	1.756
Size of Giant	-	-	-	4	4	10
No. of Stars	-	-	-	1	1	2

Table 3: The number of star networks, linked star networks and interlinked hubs

Period	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
No. of stars networks	3	14	27	89	233	312
No. linked star networks	2	10	17	62	142	174
No. linked hub firms	1	7	10	44	99	113

Table 4: Size and Number of Complete Networks (RJVs) of Size 3 or Greater

Period	*1899-1944*	*1945-1959*	*1960-1969*	*1970-1979*	*1980-1989*	*1990-2000*
3 Firms	2	1	3	6	11	23
4 Firms	-	-	1	-	2	5
5 Firms	-	-	-	-	-	2
7 Firms	-	-	-	-	-	1

Table 5: Topological Comparison of Random Network and R&D Network

Period	*1899-1944*		*1945-1959*		*1960-1969*		*1970-1979*		*1980-1989*		*1990-1999*	
Network	Actual	Random	Actual	Random	Actual	Random	Actual	Random	Actual	Random	Actual	Random
Number of Firms	33		61		225		592		1601		2348	
Number of Links	46	48	62	63	264	244	686	709	2271	2527	3090	2667
Average Degree	2.788	2.909	2.033	2.066	2.347	2.169	2.318	2.395	2.837	3.157	2.632	2.272
Density	0.087	0.091	0.034	0.034	0.011	0.009	0.004	0.004	0.002	0.002	0.001	0.001
Cluster. Coeff't	0.409	0.091	0.271	0.033	0.245	0.012	0.196	0.005	0.197	0.001	0.191	0.0002
Size of Giant	10	31	10	51	93	192	354	522	1071	1511	1402	2024

Table 6: Analysis of Fault Tolerance and Stability of the R&D Network

Period	*1899 - 1944*	*1945 - 1959*	*1960 - 1969*	*1970 - 1979*	*1980 - 1989*	*1990 - 1999*
Network Size	33	61	225	592	1, 601	2, 348
Firms Removed	2	3	11	30	80	117
Size of Giant						
Actual (% of Netwk.)	10 (30.3%)	10 (16.4%)	93 (41.33%)	354 (59.8%)	1, 071 (66.9%)	1, 402 (59.7%)
Random (% of Netwk.)	9 (29.3%)	8 (14.3%)	85 (37.8%)	297 (52.2%)	918 (63.7%)	918 (43.1%)
Connected (% of Netwk.)	6 (20.7%)	10 (17.5%)	32 (15.7%)	47 (9.7%)	269 (21.2%)	269 (14.5%)
Average Distance						
Actual	1.356	2.956	4.909	5.698	4.963	5.026
Random	1.4	2.3	5.84	5.797	5.08	5.0629
Connected	1	2.956	4.296	4.723	9.107	6.5212
Cl. Coefficient						
Actual	0.409	0.271	0.245	0.196	0.197	0.191
Random	0.35	0.259	0.244	0.194	0.19	0.1875
Connected	0.42	0.243	0.24	0.1659	0.1615	0.1556

Table 7: Network Statistics for the Most Highly Connected (Highest Degree) Firms.

Period	Firm Name	Degree	Size 2nd Order Neighborhood	Clustering Coefficient
1899-1944	TEXACO	8	7	0.75
	S-OIL-NJ	8	7	0.75
	SHELL	7	8	1
	ARCO	7	8	1
	ELF-AQUI	7	8	1
	MOBIL	7	8	1
1945-1959	MITSUBIS	6	4	0.667
	KAWASAKI	5	5	1
	FUJI-HI	5	5	1
	SHIN-MI	5	5	1
	JAPAN-A	5	5	1
	SHOWA-A	5	5	1
1960-1969	VEBA	14	28	0.4725
	BAYER	13	31	0.359
	DOW	12	26	0.4242
	MITSUBIS	12	13	0.3182
	SHELL	10	35	0.6444
	BASF	9	26	0.7778
	DSM	9	26	0.7778
	SOLVYA	9	26	0.7778
1970-1979	MITSUBIS	31	61	0.0624
	MITSUI	22	90	0.0563
	SHELL	21	95	0.219
	BP	19	82	0.1228
	AKZO	18	79	0.0784
	SIEMENS	16	39	0.0583
	SUMITOM	15	58	0.0762
	DOW	15	43	0.2762
1980-1989	MITSUBIS	85	351	0.0389
	MITSUI	64	317	0.0615
	PHILIPS	53	189	0.0226
	SUMITOMO	44	268	0.0772
	DOW	33	204	0.1004
	SHELL	32	301	0.131
	GE	31	248	0.071
	OLIVETTI	31	140	0.0237
	ICI	29	154	0.0296
1990-1999	MITSUBIS	91	437	0.0471
	MITSUI	67	389	0.0647
	PHILIPS	56	276	0.0221
	SUMITOMO	52	324	0.0573
	IBM	40	202	0.0538
	DOW	34	248	0.098
	AKZO	32	242	0.0363
	HITACHI	32	313	0.1532

Figure 1: The star network centered on Shell Oil in the period 1970-1979

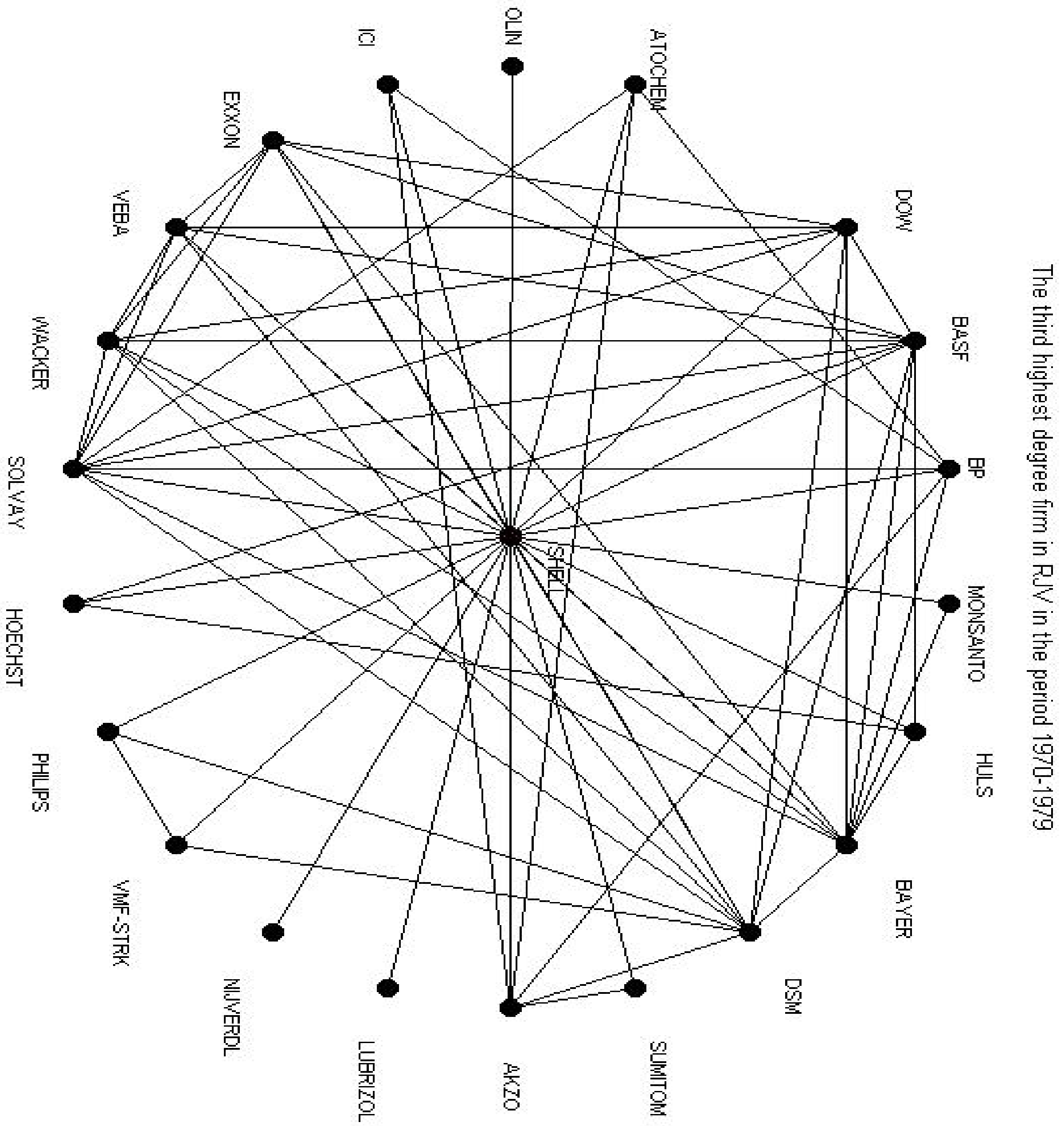

Figure 2: Star Network for Philips in the period 1980-1989

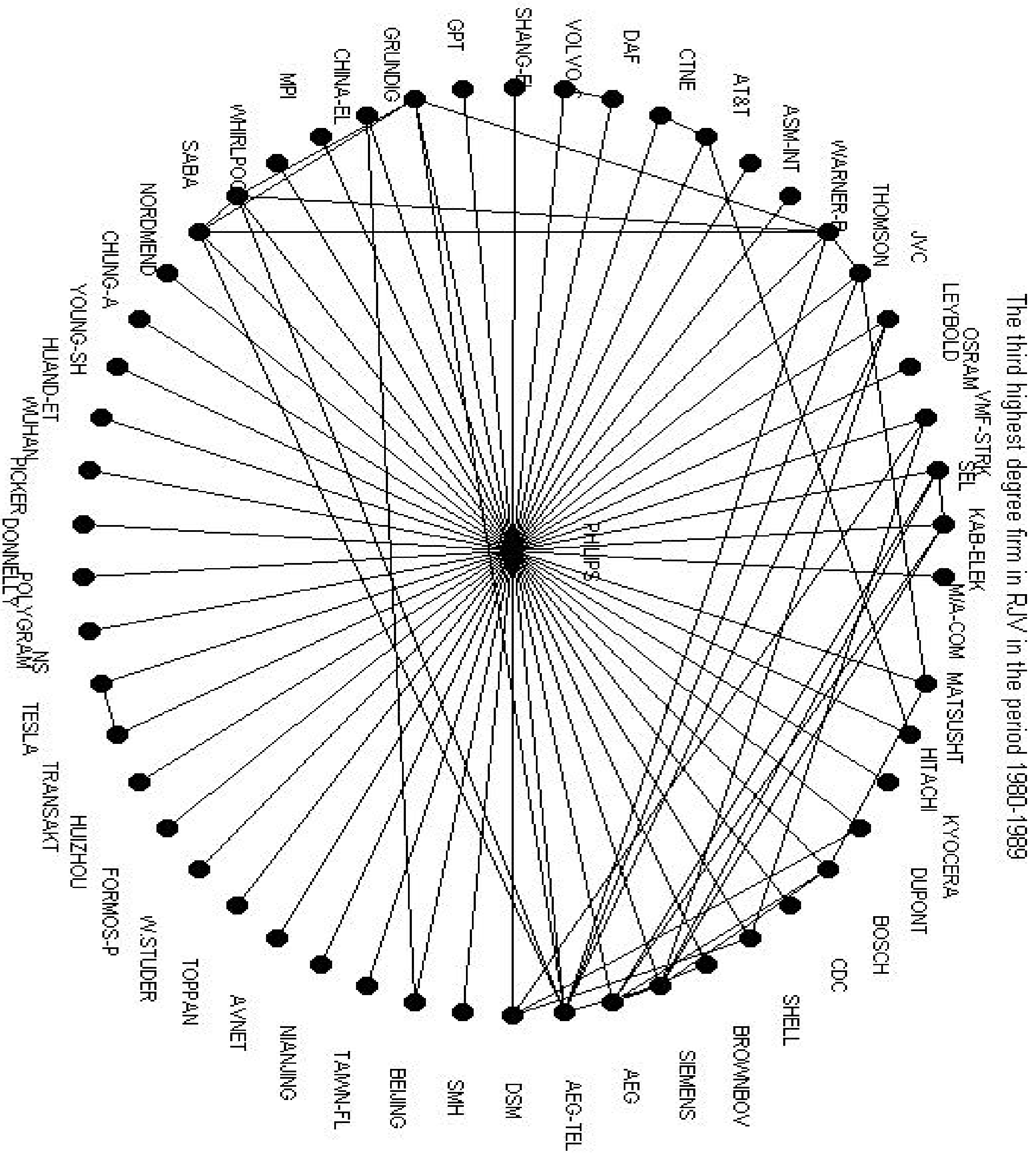

Figure 3: The star network centered on the Sumitomo Corporation in the period 1980-1989.

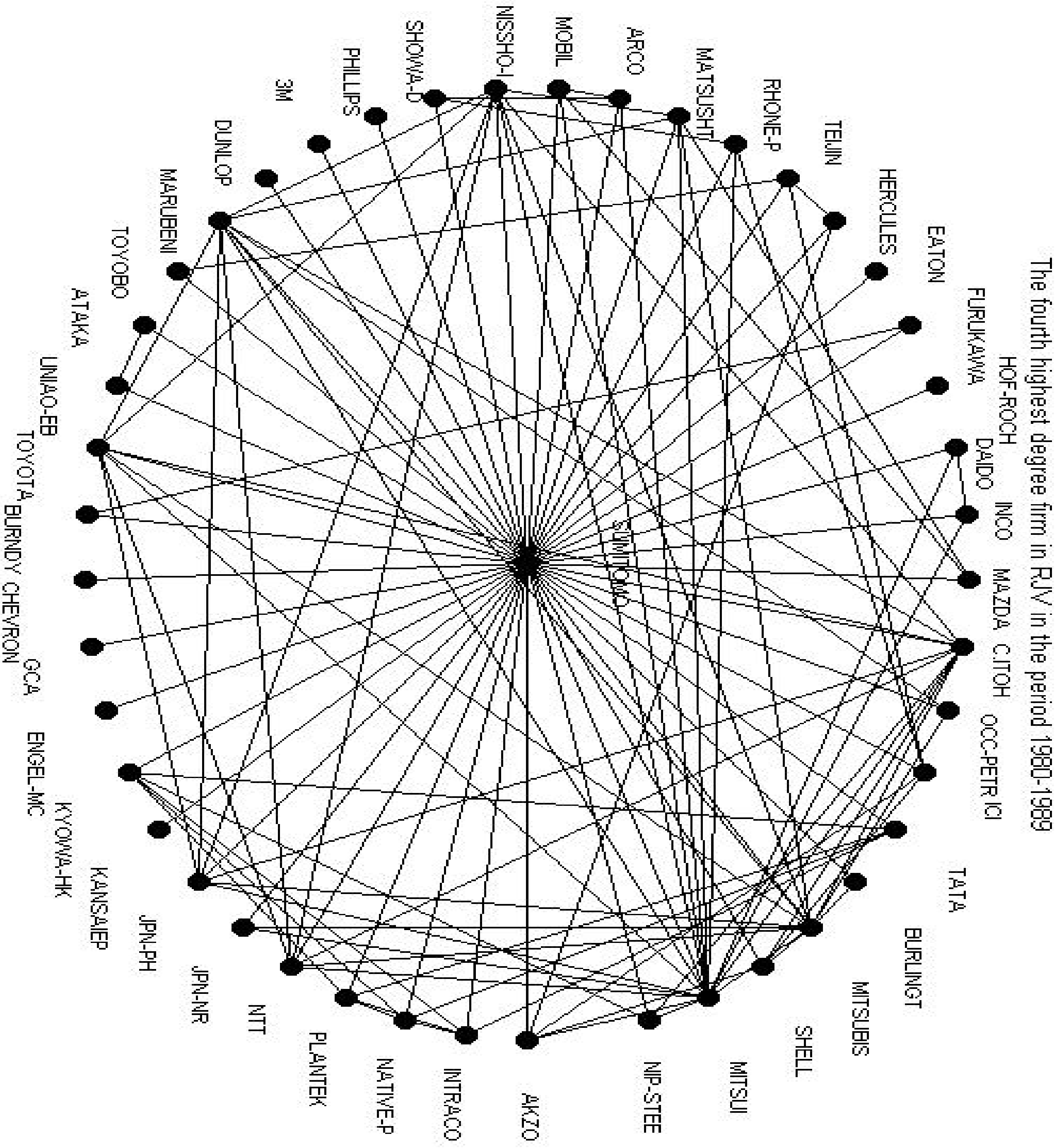

Figure 4: The star network centered on the Sumitomo Corporation in 1990-1999.

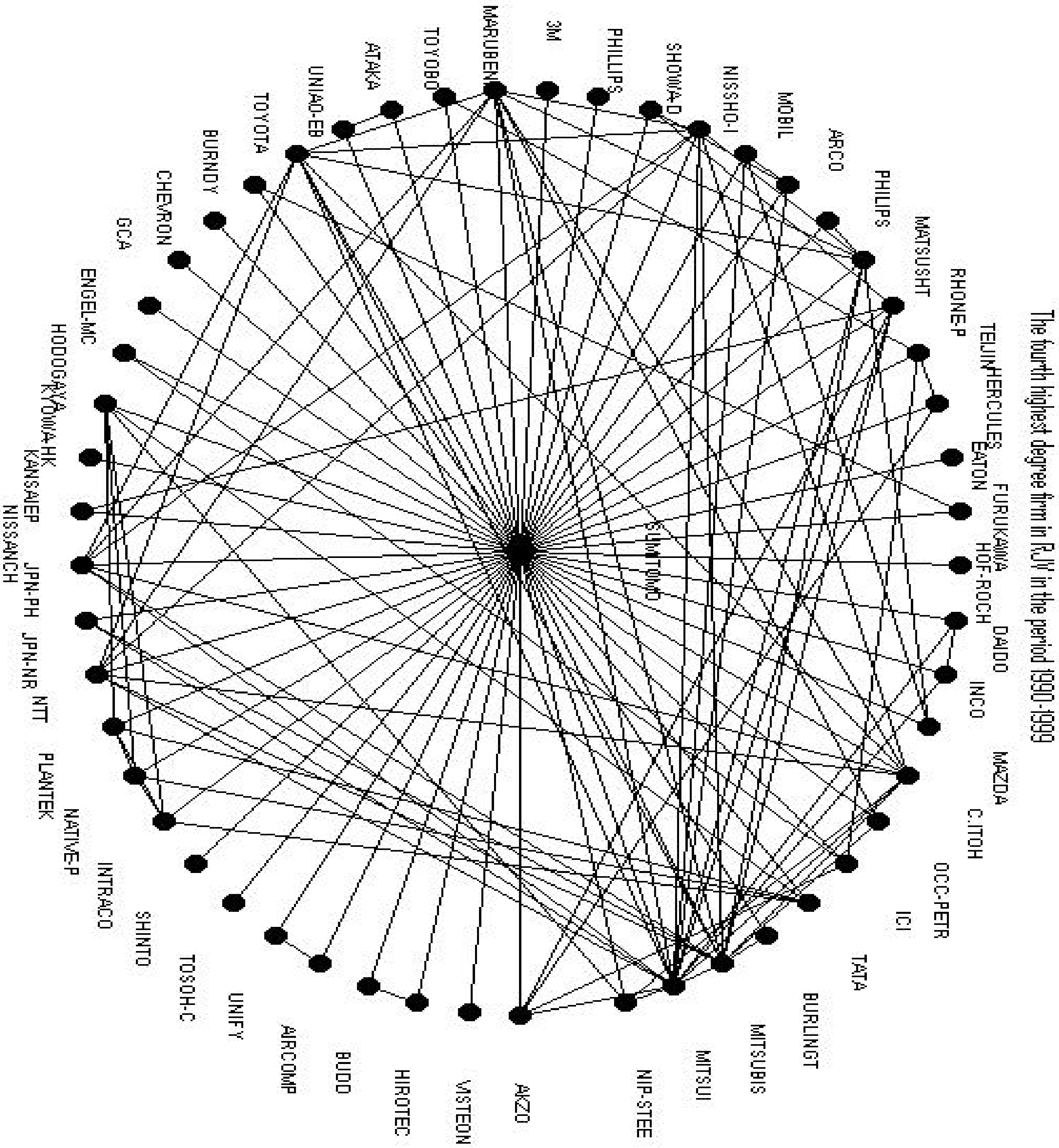

Figure 5: The star network centered on IBM in the time period 1990-1999.