Science grows and cumulates on the research fronts of disciplinary specialties, implying that the most fruitful citation analyses will be those looking at well-defined specialties or subspecialties. The entire literature on centrality and productivity from 1948 to 1979 is used to construct a citation network. Methods are proposed for the analysis of the connective structure of such networks and then applied to the centrality-productivity citation structure. These methods permit identification of the main paths through this literature, distinct intellectual phases, and key articles contributing to the cumulative formation of knowledge about centrality and productivity in social networks. From 1948 through 1956, centrality and program were integrated in a single research program. By the early 1960s, there were two research streams. One focused on measuring centrality in graphs but lost the substantive focus on productivity. The other branch continued the experimental focus on productivity but lost the idea of centrality.

Analyzing the Structure of the Centrality-Productivity Literature Created Between 1948 and 1979

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Connectivity methods (Hummon & Doreian, 1989) for the analysis of citation networks are founded on three simple ideas:

1. Science is a cumulative venture where each new discovery or development depends on some prior work.

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2. The products are generated at the research fronts of specialty fields.
3. The written record, in the form of citation networks, that is left after a research front moves on contains valuable information for understanding the processes of science.

One product of the analysis of citation networks is the widely known image of science as a mosaic of connected networks (Narin, Carpenter, & Berlt, 1972). Each field or specialty has its own citation network, and these networks are loosely linked to form the mosaic of science. The density of citation ties within a specialty or field is likely to be higher than the density of ties connecting it to the rest of the scientific literature.

Small and Griffith (1974) show how citation networks can be mapped into partly overlapping and connected specialties. They start with a network encompassing multiple specialties and delineate the boundaries between the specialties. Starting a search strategy *within* a specialty also permits the determination of its effective boundary. Ideas are less likely to travel across this boundary in either direction. As research is done within specialties, the citation structure within them reveals, among other things, their cognitive structures.

Bernal (1953) may have been the first to construct a network diagram having nodes as scientific productions (within a specialty) and links representing citations between the productions (Garfield, 1979). Garfield, Sher, and Torpie (1964) constructed such a diagram, calling it a historiograph, and used it to study the unfolding of the DNA literature. For small historiographs, the visual representations of the links in the literature in the form of a network have great appeal. However, if a network has hundreds or thousands of research productions, the visual clarity rapidly disappears. It is important, then, to augment the graphs with some computational procedures for analyzing the structure of the network.

The methods based on depth first search, exhaustive search, and priority search algorithms provide such a tool (Hummon & Doreian, 1989). The historiographs contain the time-dependent linkages between scientific events that underlie the cumulative development of knowledge. Using the DNA research literature as a test case, Hummon and Doreian (1989) were able to delineate the main path through this historiograph. Even though the algorithms are structural, responding only to the structure of citations, all the historically noted major developments in DNA research fell on this main path. Other important work was close to the main path, whereas marginal work was located at the periphery of the specialty.

Although the clarity of the results was stunning, one drawback of that analysis stems from the network published by Garfield et al. (1964) and repeated in Garfield (1979), having been highly edited. There are 40 nodes in that network, constructed from 69 scientific productions, and it is clear that the research literature of such a field is much larger than this. The Institute for Scientific Information (ISI) account was predicated on the history written by Asimov (1963) in *The Genetic Code.* Asimov provided the first editing, and the ISI research team provided the second. It is possible that the simple elegance of the main path analysis in the DNA network is an artifact arising through the simplification of a highly complex citation network.

In order to have a serious examination of the utility of connectivity methods, it is necessary to apply them to other citation networks. It is clear that such networks should be larger and, moreover, not pruned in the radical and extensive way that the DNA network was pruned. In order to satisfy the second property, the citation network should be focused on a specialty literature. Moreover, all the relevant research productions must be included.[1] Rather than defining "network analysis" as a research area (one that is rapidly growing, is quite highly developed, rests on many disciplines, and has a vast literature), we have elected to focus on the specific part of that literature dealing with centrality and productivity.

The Centrality-Productivity Literature

The Bavelas article "A Mathematical Model for Group Structures" (1948) remains one of the high-water marks in the social network literature. Bavelas's work is very important for the field for at least three reasons:

1. By varying the communication structure of task-oriented groups, he was able to show how different networks with different structural characteristics would lead to different times for the completion of a specific task.[2] The structure of the network conditions the outputs that result from network processes.
2. He showed also that the structural location of an actor in a network makes a difference, as the actors view themselves, and the group task, differently depending on whether they are at the center or the periphery of the small-group communication structure.
3. The dramatic effects of this research spawned a literature covering at least four decades. Centrality—with or without productivity—became an enduring concern.

Research productions in this literature have some, or all, of the following elements: social psychological small-group processes, experimental design, social organization, business administration, and measurement. Linking the

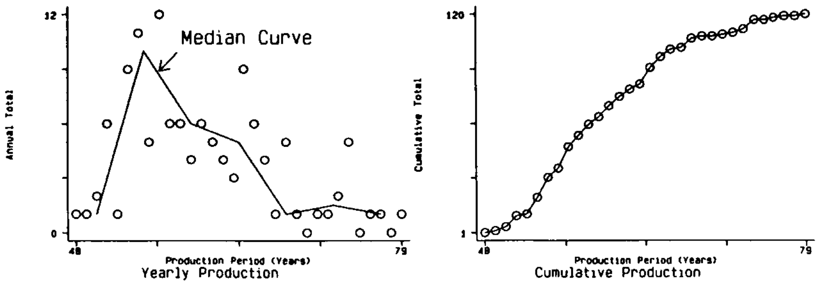

Figure 1: Annual and Cumulative Production by Centrality Group

research together is the common focus on the issue of centrality and its implications for network processes. This research specialty has an obvious starting point in the work of Bavelas (1948, 1950). There is also a clear endpoint to a particular *phase* of research dealing with centrality. Although the intuitive idea of centrality is clear, its precise operationalization has been confused. Freeman (1977, 1979) cleared up the confusion by pointing out three distinct operationalizations of centrality (and pointing out that fruitful use of the concept rests on clear, substantively relevant operationalizations). The data base for the following connectivity analysis is made up of *all* publications on the topic of centrality and productivity that appeared between the Bavelas and Freeman articles.[3]

The data base contains 119 articles, technical reports, or books that were created between 1948 and 1979. For the analysis reported here, we have excluded unpublished Ph.D. dissertations and unpublished master's dissertations but not review papers. We have specifically included many technical reports that, though unpublished, may have been critical to the evolution of this specialty.[4]

Figure 1 provides information on the annual production of the centrality group and the cumulative production through the period from 1948 to 1979. It is clear from the left panel of Figure 1 that most of the production took place during the 1950s and production tailed off after that, particularly in the 1970s. The cumulative production has the general S-curve that Crane (1972) sees as a characteristic of research specialties, although, in part, this is an artifact of plotting cumulative data. There are 632 citation links between the 119 research productions generated by this research group. At the outset (1948) it was not clear which publications would prove to be important, as that can be determined only by later publication activity. We emphasize that science is cumulative and the research literature of an area has structure — the *structure* created by the *evolution* of knowledge.

This knowledge is produced in a "theory group" as described by Mullins (1973). Mullins delineates four stages: (1) normal, (2)network, (3) cluster, and (4) specialty or discipline. The most important aspect of the development process for a specialty is the "communication structure" of the research group. It is a straightforward process to show that the centrality-productivity area appears to conform to the stages and processes described by Mullins. This communication is located in the citation network, and these links can be treated solely as citation links in a network of citations (compare Price, 1965). The links suggest the passage of theoretical ideas, experimental design, empirical results, modeling strategies, or any combination of them. There is bound to be random error, some because of suspect citation, but it is highly likely that such errors will be seen as the random events they are.

Connectivity Methods

The centrality-productivity literature network is complete, as all known citations among these research productions are included. The network has 119 nodes and 630 links. The relation of this network is the "is cited by" relation instead of the "cites" relations. The "is cited by" network maps the influence of earlier research on later research.

The network of literature on centrality and productivity has the following properties. First, it is completely, though weakly, connected.[5] Second, the network is nearly a directed acyclic graph, or DAG. It contains only two cycles involving productions having the same author or close members in a single geographical location.[6]

Another way of examining connectivity in such a network is to compute the path distances between node pairs. The geodesic, or minimum path, is commonly used to assess how close nodes are to each other, in a graph theoretic sense.[7] Starting from node 1 (the Bavelas article),[8] the maximum geodesic is three, and most geodesics are only one link. The maximum geodesic for the whole network is only five. This high degree of connectedness may be due to the completeness of this citation network.

Geodesics, or minimum paths, are not very relevant to a model of science that assumes knowledge is accumulated step by step. Instead, maximum path lengths or graph tours are of interest. The longest path for the centrality network is, as would be expected, more complex than for the DNA network. This path has 16 links and occurs only once, extending from node 1 to node 131.

Network Connectivity and Search Paths

The exhaustive search algorithm can be used to generate all possible search paths through the network. The count of the number of times a link is traversed by all possible search paths is a measure of the importance of that link. These traversal counts are analogous to the counts of the number of geodesics that run through a node in Freeman's centrality measure. However, we are concerned with the connectivity of the links rather than the centrality of the nodes. As discussed earlier (Hummon & Doreian, 1989), we compute traversal counts in three ways: search path link count (SPLC), the search path node pair (SPNP), and the node pair projection count (NPPC). Briefly, the SPLC method is a simple count of the number of times links are members of all possible search paths for the network. The SPNP method is similar to SPLC except that only search paths that connect particular pairs of nodes are considered. The NPPC method constructs a network of search paths that connect each node pair and then projects the set of all search path networks onto a base network. For this dense centrality network, two links share the highest traversal count of 226,780: the link from node 1 to node 6 and the link from node 130 to node 131 — the first and last links in the network.

The traversal counts can be used to define the main path through a citation network. From any node, we examine the traversal counts of links leaving the node. We choose the link with the highest traversal count and proceed to the next node over that link. We repeat the process until we reach a terminal node.[9] In this manner, we define a path through the network that follows the structurally determined most-used path. We label this path the main path through the network. This link selection technique is an example of the priority first search algorithm, where traversal counts set the priority.

Our intuition is that the main path, selected by the most-used path, will identify the main stream of the literature. Table 1 gives the main path through the centrality literature. It starts with node 1 (the Bavelas article), and one branch *finishes* with node 131 (the Freeman article), as also shown in Figure 2. However (see note 9), the main path from node 2 terminates in node 118. Although by definition *the* main path for the *whole* structure must start at node 1, some attention should be given to paths terminating at node 118.

The early part of this main stream focuses on experimental studies of social psychological processes in task-oriented groups and runs from node 1 through node 50. After node 50, the main path branches into two streams. Using search path link count (SPLC) and search path node pair (SPNP) connectivity methods, the next node in the main path is node 59, as shown

TABLE 1
The Main Paths Through the Centrality-Productivity Literature

1. Bavelas (1948)
6. Leavitt (1951)
9. Heise & Miller (1951)
24. Shaw (1954c)
22. Gilchrist, Shaw, & Walker (1954)
21. Shaw (1954b)
33. Shaw (1955)
50. Shaw & Rothschild (1956)

59. Flament (1958b)	84. Cohen, Bennis, & Wolkon (1961)
81. Flament (1961)	88. Cohen, Bennis, & Wolkon (1962)
90. Flament (1963)	87. Cohen & Bennis (1962)
104. Beauchamp (1965)	95. Cohen (1964b)
109. Sabidussi (1966)	98. Cohen (1964)
126. Moxley & Moxley (1974)	113. Cohen (1967)
130. Freeman (1977)	118. Cohen & Foerst (1968)
131. Freeman (1979)	

in the left part of Table 1. However, using the node pair projection methods (NPPC), the next node is node 84, as shown in the right part of Table 1. The relative traversal counts by all three methods are close for these two choices. In our experience, this is unusual, because main path node selections are usually clear. We conclude that this split in the main path is significant.

With the work of Flament (node 59), the left branch of the main path undergoes a radical transformation. Node 59 marks the transition from a focus on the implications of centrality for group productivity to an explicit concern with measurement of centrality. Following node 59, all articles focus on the definition and measurement of centrality. This was a noteworthy transition. Within Bavelas's work there is a major ambiguity about centrality. As Freeman (1979) points out, degree centrality, nearness centrality, and betweenness centrality are distinct and need to be distinguished if the structural consequences of centrality are important. Throughout the early phase of the main path, the major thrust and inventiveness came in the design of variations of the fundamental experiment. However, these researchers did not probe deeply the meaning of centrality.

The right branch in the main path after node 50 continues the experimental study of productivity in small groups and culminates at node 118. As time passed, the work of these experimentalist exhibited less and less concern with centrality and, more generally, with the structural *properties* that led to their results. The experimental structures were assigned names, and the results were couched in terms of the relative performance of "wheels," "stars," and so forth. In effect, after the work of Shaw and Rothschild (node 50), the earlier tradition that integrated work on centrality with work on productivity split into two research streams. One group worked on centrality while the other worked on productivity.

Another way to examine the structure of the main path or paths through a citation network is to construct the network of main paths. We compute a main path from every nonterminal node in the network. We then use the links in these paths to define the network of main paths. Figure 2 presents part of this network,[10] whereas using NPPC yields Figure 3.[11] Seventy percent of all nodes have main paths that end at either node 131 or node 118.

Structural Equivalents

We also analyzed the centrality literature network for structural equivalents. If two articles cite the same earlier articles, then, in the sense of bibliometric coupling, they are equivalent. Alternatively, if they are cited by the same other articles, they are, in the cocitation sense, equivalent. Of course, research productions can be equivalent in both the bibliometric coupling and the cocitation sense. We computed the extent of nonequivalence as measured by Euclidean distance and then clustered the nodes of the network. An icicle plot (Kruskal & Landwehr, 1983) was used to examine the clustering results.

Using the icicle plot, we split the set of articles into three groups. All the members of the first group are either unpublished, not written in English, or both. Their location in the icicle plot shows that they are peripheral to the

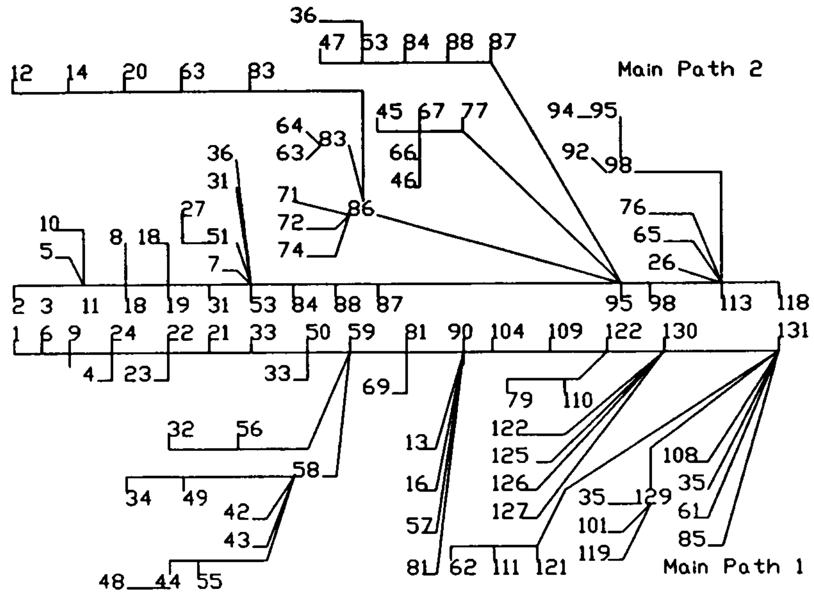

Figure 2: SPLC Main Path Networks

determination of a main path. Moreover, they are irrelevant to the development of this scientific field. As Mullins (1973) points out, a theory group needs a geographical location (or an intellectual one) where a group of scholars freely exchange papers and provide mutual criticism. In terms of the recognition in defining a specialty, it is clear that published work is more important than unpublished work even if the unpublished work helps create a cultural milieu within which science can be conducted.

The second group of articles shows some kind of coherence in the sense of the stepping-up pattern to the right. These works form the bulk of the literature and are the "journeyman" products in that literature. They are more relevant than the unpublished productions, but very little distinguishes them concerning the contribution in creating scientific knowledge.

The third group of articles is not so much a cluster, in the cluster analytic sense, but a group containing most of the discontinuities in the icicle plot. *All of the main path nodes are found within this third group.* This pattern of main path nodes and significant jumps in clustering levels describes the structural nonequivalence properties of the third group.

If this interpretation is correct, then nodes on the main path are quite unlike other nodes in the network. They demarcate important transitions in the

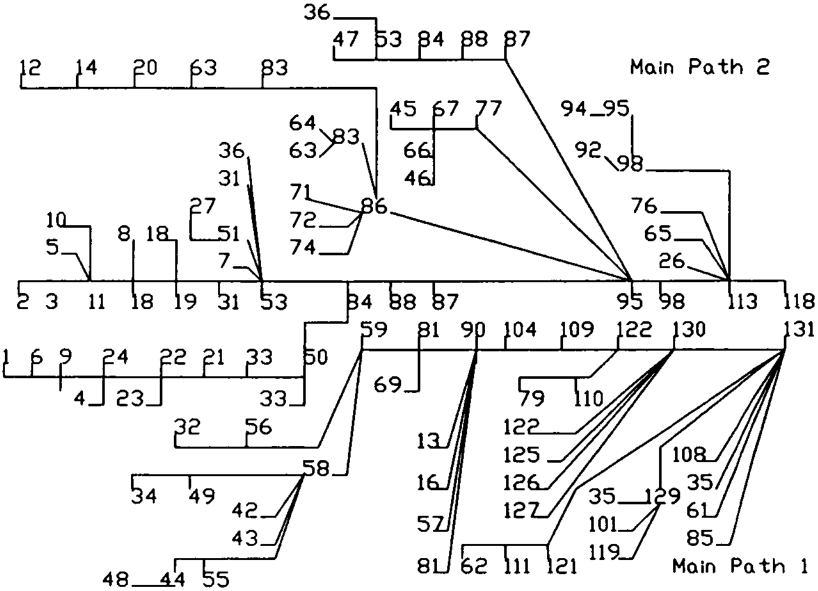

Figure 3: NPPC Main Path Networks

literature and represent the critical blocks from which the specialty generates its knowledge.[12]

This analysis suggests an image of the literature of a specialty as a watershed in an ecological system. Articles belong to a particular niche and funnel knowledge into the streams of the literature. Ideas that are not picked up quickly within a watershed are not absorbed, and nothing distinguishes them from one another. This seems to be the fate of the works in Group 1. Other items may be important as minor tributaries within a watershed, which characterizes most of the work in Group 2. Finally, there are the main waterways of each watershed. Ideas near the main path are picked up quickly and augment the main stream.

The major knowledge bases for this (centrality-productivity) specialty can be found in social psychology, communications, and organization theory. We coded each research production according to the presence or absence of these properties. We found no differences in the relative distribution of these characteristics across the different cluster groups. Further, the presence or absence of experimental methods does not distinguish the three cluster groups. However, when we consider the presence or absence of graph theory, the three groups have different distributions; see Table 2.

TABLE 2
Relevance of Graph Theory and Publication, and the Decade of Production

Group	*Graph Theory* Absent	Present	Total
1	25 25.77%	6 27.27%	31 26.05%
2	29 29.90	1 4.55	30 25.21
3	43 44.33	15 68.18	58 48.74%
Total	97 100.00%	2 100.00%	119 100.00%

$\chi^2(2) = 6.68$ Prob > $\chi^2 = 0.035$

(1) Distribution of Graph Theory Presence by Group

Group	*Published* No	Yes	Total
1	14 58.33%	17 17.89%	31 26.05%
2	9 37.50	21 22.11	30 25.21
3	1 4.17	57 60.00	58 48.74
Total	24 100.00%	95 100.00%	119 100.00%

$\chi^2(2) = 26.08$ Prob > $\chi^2 = 0.000$

(2) Distribution of Publication Outcome by Group

The presence of graph theory intensifies through the three identified groups, so that graph theory enjoys the highest relative frequency within the set of publications seen as crucial. We have seen (Table 1) that the centrality-productivity literature split into separate literatures. The branch continuing the experimental approach to productivity, but without the structural concept

TABLE 2 Continued

Decade	Published: No	Published: Yes	Total
1940-49	1 4.17%	1 1.05%	2 1.68%
1950-59	19 79.17	40 42.11	5 49.58
1960-69	4 16.67	42 44.21	46 38.66
1970-79	0 0.00	12 12.63	12 10.08
Total	24 100.1%	95 99.9%	119 100.1%

$\chi^2(3) = 13.20$ Prob $> \chi^2 = 0.004$

(3) Distribution of Publication Outcome by Group

of centrality, appears to have run its course. As such, it offers no foundation for future work.[13] The other branch, whose primary focus was on centrality, almost to the exclusion of substantive concerns, seems to have prevailed. This is not a triumph of technique over substance, as both branches of the main path lost a key concern. Rather, with centrality conceptualized clearly, the way is clear to examine its substantive implications.

Summary

Connectivity methods (Hummon & Doreian, 1989) provide a coherent way of examining the connective structure of scientific citation networks. When these methods are used for the complete set of productions dealing with centrality and productivity, a very clear main path is found. It starts with an article by Bavelas in 1948 and follows a course where centrality and productivity are both considered. By the late 1950s, this main path had split into two distinct parts. One branch continued the experimental examination of productivity but lost the conception of centrality as a structural property. The other path underwent a transformation to the use of graph theory for defining and measuring centrality and thereby lost the substantive concern with productivity. By establishing the main path with a bifurcation, connectivity methods have revealed distinct intellectual phases in the study of centrality and productivity.

An appropriate next step is to consider the centrality literature published since 1979 to delineate the main paths from the Freeman article. Our intuition is that at least two branches will be seen. One will explore the substantive implications of centrality across a wide range of social phenomena; the other will continue the graph theoretical work. The former branch will reintegrate a structural concept of centrality with issues of substance. Both branches can be studied with the citation data from 1979 onward or with the combination of the pre- and post-1979 data.

APPENDIX

Productions of the Centrality-Productivity Literature

Note: For each research production the last number, in parentheses, is its identification number.

Bavelas, A.
1948 A mathematical model for group structures. Applied Anthro. 7:16-30. (1)

Bavelas, A.
1950 Communication patterns in task-oriented groups. J. Acoustical Soc. Amer. (4) 22: 725-730. (4)

Bavelas, A. and D. Barrett
1951 An experimental approach to organizational communication. Personnel. 27:366-371. (8)

Beauchamp, M.
1965 An improved index of centrality. Behavioral Science. 10:161-163. (104)

Burgess, R. L.
1963 Communication networks and behavioral consequences. Human Relations. 22:137-159. (Review) (116)

Burgess, R. L.
1968a Communication networks, behavioral consequences and group learning. Unpublished Ph.D. dissertation. St. Louis: Washington University. (117)

Burgess, R. L.
1968b Communication networks: An experimental re-evaluation. Journal of Experimental Social Psych. 4:324-337. (114)

Burgess, R. L.
1968c An experimental and mathematical analysis of group behavior within restricted networks. Journal of Experimental Social Psych. 4:338-349. (115)

Carzo, R.
1963 Some effects of organization structure on group effectiveness. Admin. Sci. Quart. 7:393-424. (91)

Christie, L. S.
1954a Organization and information processing. Navy Systems Analysis Project Report No. 1954-494-03-25, Tufts College, Medford, Mass. (30)
Christie, L. S.
1954b Organization and information handling in task group. J. Operations Res. Soc. Amer. 2:188-196. (31)
Christie, L. S. and R. D. Luce
1954 Suggestions for the analysis of reaction times and simple choice behavior. Control Systems Laboratory Report R-53, University of Illinois, Urbana, Ill. (28)
Christie, L. S., R. D. Luce and J. Macy
1952 Communications and learning in task oriented groups. Cambridge, Mass.: Research Lab. of Electronics. Tech. Report No. 231. (11)
Christie, L. S., R. D. Luce and J. Macy
1956 Information handling in organized groups, in J. F. McCloskey and J. M. Coppinger (eds.). *Operations Research for Management Vol. II: Case Histories, Methods, Information Handling.* Baltimore: Johns Hopkins Press: 417-537. (39)
Christie, L. S. and C. S. Morrill
1954 The assessment of attitudes relevant to team performance. Navy Systems Analysis Project Report No. 1954-494-03-26, Tufts College, Medford, Mass. (29)
Cohen, A. M.
1961 Changing small group communication networks. Journal of Communications. 11: 116-124, 128. (82)
Cohen, A. M.
1962 Changing small-group communications networks. Admin. Sci. Quart. 6:443-462. (86)
Cohen, A. M.
1964a Communication networks in research and training. Personnel Administration. 27:18-24. (Review) (98)
Cohen, A. M.
1964b Predicting organization in changed networks II. Journal of Psych. 57:475-499. (94)
Cohen, A. M.
1964c Predicting organization in changed networks III. Journal of Psych. 58:115-129. (95)
Cohen, A. M.
1967 A model of group adaptation to organizational change in communication networks, in L. O. Thayer (ed.) Communication: Theory and Research. Springfield, Ill.: Charles C Thomas: 28-74. (113)
Cohen, A. M. and W. G. Bennis
1960a The effects of an elective situation on continuity of leadership under conditions of change in work structure. Boston U. Human Relations Center. Technical Report. (72)
Cohen, A. M. and W. G. Bennis
1960b A model predicting the influence of previous experience on the communication systems established by problem-solving groups. Boston U. Human Relations Center. Technical Report. (73)
Cohen, A. M. and W. G. Bennis
1961 Continuity of leadership in communication networks. Human Relations. 14:351-367. (83)
Cohen, A. M. and W. G. Bennis
1962 Predicting organization in changed communication networks. Journal of Psych. 54:391-416. (87)

Cohen, A. M., W. G. Bennis and D. Briggs
1960 A partial test of a model predicting the influence of previous experience on the communication systems established by problem-solving groups. Boston U. Human Relations Center. Technical Report. (76)
Cohen, A. M., W. G. Bennis and G. H. Wolkon
1960 The effects of position changes in communication patterns on the behaviors of problem-solving groups. Boston U. Human Relations Center. Technical Report. (71)
Cohen, A. M., W. G. Bennis and G. H. Wolkon
1961 The effects of continued practice on the behaviors of problem-solving groups. Sociometry. 24:416-431. (84)
Cohen, A. M., W. G. Bennis and G. H. Wolkon
1962 The effects of changes in communication networks on the behaviors of problem-solving groups. Sociometry. 25:177-196. (88)
Cohen, A. M. and J. R. Foerst
1968 Organizational behavior and adaptation to organizational change of sensitized and repressor problem-solving groups. Journal of Personality and Social Psych. 8:209-216. (118)
Cohen, A. M., P. E. Rosner and J. R. Foerst
1973 Leadership continuity in problem-solving groups: An interactional study. Human Relations. 26:753-774. (123)
Collins, B. E. & B. H. Raven
1969 Group structure: Attraction, coalitions, communication, power, in G. Lindzey & E. Aronson (eds.) *Handbook of Social Psychology* (2nd ed.) vol. 4 Reading, Mass.: Addison-Wesley. (Review) (119)
DeSoto, C. B.
1953 The effects of imposed authority status in a wheel group structure. Unpublished M. A. thesis. University of Wisconsin. (14)
Doktor, R. and S. Makridakis
1974 Computer simulation of the communication network experiments: An application of stability theory. General Systems. 19: 195-199. (124)
Faucheux, C. and K. D. MacKenzie
1966 Task dependency of organizational centrality: Its behavioral consequences. Journal of Experimental Social Psych. 2:361-375. (111)
Faucheux, C. and S. Moscovici
1960 Etudes sur la créativité des groups tâche, structures des communications et réussite. Bulletin du C.E.R.P. 9:11-22. (79)
Flament, C.
1956a Changements de rôles et adaptation latâche dans des groupes de travail utilisant divers reseaux de communication. Année. Psych. 56:411-432. (42)
Flament, C.
1956b Influence des changements de réseaux de communication sur les performance des groupes. Psychologie Francais. 1:12-13. (Review) (43)
Flament, C.
1958a La performance des groupes de travail rapports entre la structure de l'activité et celle du le seau de communication. Année Psych. 58:71-89. (58)
Flament, C.
1958b Performance et reseaux de communication. Bulletin du Centre d'Etudes et de Recherches Psychotechniques. 7:97-106. (59)

Flament, C.
1960 L'étude structurale des groupes. Bulletin de Psychologie. 123:417-425. (Review) (69)
Flament, C.
1961 Processus d'influence sociale et réseau de communication. Psych. Francaise. 6:115-125. (81)
Flament, C.
1963 Applications of graph theory to group structure. Englewood Cliffs, N.J.: Prentice-Hall. (90)
Flament, C.
1965 Réseaux de communication et structures de groups. Paris: Dunod. (Review) (108)
Freeman, L. C.
1977 A set of measures of centrality based on betweenness. Sociometry. 40:35-41. (130)
Freeman, L. C.
1979 Centrality in social networks: I. Conceptual clarification. Social Networks. 1:215-239. (131)
Gilchrist, J. C., M. E. Shaw and L. C. Walker
1954 Some effects of unequal distribution of information in a wheel group structure. J. Abnorm. Soc. Psych. 49:554-556. (21)
Glanzer, M. and R. Glaser
1961 Techniques for the study of group structure and behavior II. Empirical studies of the effects of structure in small groups. Psychol. Bull. 58:1-17. (Review) (85)
Goldberg, S. C.
1955 Influence and leadership as a function of group structure. J. Abnorm. and Soc. Psych. 51:119-122. (32)
Guetzkow, H.
1951 Organizational development and restrictions in communication. Dittoed paper, Carnegie Institute of Technology, 108 pp. Reprinted-unpublished manuscript. American Documents Institute, No. 4590. (71)
Guetzkow, H.
1954 Organizational development and restrictions in communications. Pittsburgh Graduate School of Industrial Administration, Carnegie Institute of Technology. (27)
Guetzkow, H.
1960 Differentiation of roles in task-oriented groups, in D. Cartwright and A. Zander (eds.) *Group Dynamics: Research and Theory (2nd ed.).* Evanston, Ill.: Row, Peterson. 683-704. (75)
Guetzkow, H. and W. R. Dill
1957 Factors in the organizational development of task-oriented groups. Sociometry. 20:175-204. (53)
Guetzkow, H. and H. A. Simon
1955 The impact of certain communication nets upon organization and performance in task-oriented groups. Mgmt. Sci. 1:233-250. (36)
Harshberger, D.
1971 An investigation of a structural model of a small group problem solving. Human Relations. 24:43-63. (120)
Heise, G. A. and G. A. Miller
1951 Problem-solving by small groups using various communication nets. J. Abnorm. Soc. Psych. 46:327-335. (9)

Hirota, K.
1953 Group problem-solving and communication. Japanese J. Psych. 24:105-113. (16)
Karaneff, V. T.
1954 Some effects of knowledge of the group structure upon the operation of the structure. Unpublished M.A. thesis, University of Wisconsin. (26)
Lanzetta, J. T. and T. B. Roby
1956a Effects of work-group structure and certain task variables on group performance. J. Abnorm. Soc. Psych. 53:307-314. (44)
Lanzetta, J. T. and T. B. Roby
1956b Group performance as a function of work distribution and task load. Sociometry. 19:95-104. (45)
Lanzetta, J. T. and T. B. Roby
1957 Group learning and communication as a function of task and structure "demands." J. Abnorm. Soc. Psych. 55:121-131. (55)
Lawson, E. D.
1964a Reinforced and non-reinforced four-man communication nets. Psychological Reports. 14:287-296. (99)
Lawson, E. D.
1964b Reinforcement in group problem-solving of arithmetic problems. Psychological Reports. 124:703-710. (100)
Lawson, E. D.
1965 Change in communication nets, performance, and morale. Human Relations. 18:139-147. (103)
Leavitt, H. J.
1949 Some effects of certain communication patterns on group performance. Unpublished Ph.D. dissertation. Massachusetts Institute of Technology. (2)
Leavitt, H. J.
1951 Some effects of certain communication patterns on group performance J. Abnorm. Psych. 46:38-50. (6)
Leavitt, H. J. and K. E. Knight
1963 Most "efficient" solutions to communication networks: Empirical vs. analytical search. Sociometry. 26:260-267. (92)
Luce, R. D.
1951 The theory of networks. Group Network Laboratory. Research Laboratory of Electronics, Massachusetts Institute of Technology. (10)
Luce, R. D., J. Macy, L. S. Christie and D. H. Hay
1953 Information flow in task-oriented groups. Research Laboratory of Electronics, Massachusetts Institute of Technology, Report No. 264. (19)
MacKenzie, K. D.
1966 Structural centrality in communications networks. Psychometrika. 31:17-25. (110)
MacKenzie, K. D.
1964 A mathematical theory of organizational structure. Ph.D. thesis. Berkeley: University of California. (102)
Macy, J., L. S. Christie and R. D. Luce
1953 Coding noise in a task-oriented group. Journal of Abnorm. and Social Psych. 48:401-409. (18)
McWhinney, W. H.
1954 Simulating the communication network experiments. Behavioral Science 9:80-84. (97)

McWhinney, W. H.
1964 Self organizing systems. Ph.D. thesis. Pittsburgh: Graduate School of Industrial Administration, Carnegie Institute of Technology. (96)
Mohanna, A. I. and M. Argyle
1960 A cross-cultural study of structural groups of unpopular central members. Journal of Abnorm. and Social Psych. 60:139-140. (76)
Morrisette, J. O.
1966 Group performance as a function of task difficulty, size and structure of group II. Journal of Personality and Social Psych. 3:357-359. (112)
Morrisette, J. O., W. H. Pearson and C. W. Switzer
1965 A mathematically defined task for the study of group performance. Human Relations. 18:187-192. (106)
Morrisette, J. O., S. A. Switzer and C. W. Crannel
1965 Group performance as a function of task difficulty, size and structure of group. Journal of Personality and Social Psych. 2:451-455. (105)
Moxley, R. L. and N. F. Moxley
1974 Determining point centrality in uncontrived social networks. Sociometry. 37:122-130. (126)
Mulder, M.
1955 De invloed van de communicatie—structuur op het gedrag van groupen. Mens en Onderneming. 9:456-469. (37)
Mulder, M.
1956 Groepsstructuur en Gedrag. Nederlands Tijdschrift voor de Psychologie. (Review) 11:85-133.
Mulder, M.
1958 Groepsstructuur, motivatie en prestatie. Den Haag: C.O.P. (Review) (61)
Mulder, M.
1959a Power and satisfaction in task-oriented groups. Acta. Psych. 16:178-225. (66)
Mulder, M.
1959b Group structure and group performance. Acta. Psych. 16:356-402. (67)
Mulder, M.
1960a Communication structure, decision structure, and group performance. Sociometry. 23:1-14. (77)
Mulder, M.
1960b The power variable in communication experiments. Human Relations. 13:241-256. (78)
Nieminen, J.
1973 On the centrality in a directed graph. Social Science Research. 2:371-378. (122)
Nieminen, J.
1974 On centrality in a graph. Scandinavian Journal of Psych. 15:322-336. (125)
Roby, T. B. and J. T. Lanzetta
1956a An investigation of task performance as a function of certain aspects of work group structure. U.S. Air Force Personnel Training Research Center. Research Report (Unpublished ms. on file, Crew Research Lab., Randolph Air Force Base, Texas) No. AFPTRC-TN-56-74. (47)
Roby, T. B. and J. T. Lanzetta
1956b Work group structure, communication, and group performance Sociometry. 19:105-113. (48)

Roby, T. B. and J. T. Lanzetta
1957a Conflicting principles in man-machine system design. J. Appl. Psych. 41:170-178. (54)
Roby, T. B. and J. T. Lanzetta
1957b A laboratory task for individual and group problem-solving behavior. Air Force personnel and Training Center Research Report.
Rogers, D. L.
1974 Sociometric analysis of interorganizational relations: Application of theory and measurement. Rural Sociology. 39:487-503. (127)
Rogers, E. M. and R. Agaruala-Rogers
1976 Communication in Organizations. New York: Free Press. (129)
Rogge, G.
1953 Personality factors and their influence on group behavior: A questionnaire study. Research Laboratory of Electronics, Massachusetts Institute of Technology, Tech. Report No. 265. (17)
Sabidussi, G.
1966 The centrality index of a graph. Psychometrika. 31:581-603. (109)
Shaw, M. E.
1953 The effects of unequal distribution of information upon leadership, morale, and problem solution efficiency in various communication nets. Unpublished Ph.D. dissertation, University of Wisconsin. (12)
Shaw, M. E.
1954a Group structure and the behavior of individuals in small groups. J. Psych. 38:139-149. (23)
Shaw, M. E.
1954b Some effects of problem complexity upon problem solution efficiency in different communication nets. J. Exp. Psych. 48:211-217. (22)
Shaw, M. E.
1954c Some effects of unequal distribution of information upon group performance in various communication nets. J. Abnorm. Psych. 49:5547-553. (24)
Shaw, M. E.
1955a Communication patterns in small groups Office of Naval Research, Research Reviews— 11-15. (Review) (34)
Shaw, M. E.
1955b A comparison of two types of leadership in various communication nets. J. Abnorm. Soc. Psych. 50:127-134. (33)
Shaw, M. E.
1956 Random vs. systematic distribution of information in communication nets. J. Pers. 25:59-69. (49)
Shaw, M. E.
1958 Some effects of irrelevant information upon problem-solving by small groups. J. Soc. Psych. 47:33-37. (60)
Shaw, M. E.
1959 Acceptance of authority, group structure and the effectiveness of small groups. J. Pers. 27:196-210. (65)
Shaw, M. E.
1964 Communication networks, in L. Berkowitz (ed.) *Advances in experimental social psychology.* New York: Academic Press, Vol. 1:111-147. (Review) (101)

Shaw, M. E. and G. H. Rothschild
1956 Some effects of prolonged experiences in communication networks. J. Appl. Psych. 40:281-286. (50)
Shaw, M. E., G. H. Rothschild and J. F. Strickland
1957 Decision processes in communication networks. J. Abnorm. Soc. Psych. 54:323-330. (56)
Shelly, M. W.
1953 THe effects of problem saturation in various communication networks. Unpublished M.A. thesis, University of Wisconsin. (20)
Shelly, M. W. and J. C. Gilchrist
1958 Some effects of communication requirements in group structures. J. Soc. Psych. 48:37-44. (57)
Shure, G. H., M. S. Rogers, I. M. Larsen and J. Tassone
1962 Group planning and task effectiveness. Sociometry. 25:263-282 (89)
Smith, S. L.
1950 Communication pattern and the adaptability of task-oriented groups: An experimental study. Group Networks Laboratory, Research Laboratory of Electronics, Massachusetts Institute of Technology. (3)
Smith, S. L.
1951 Survey of some experiments in group communication. Group Networks Laboratory of Electronics, Massachusetts Institute of Technology. (5)
Snadowsky, A.
1972 Communication network research: An examination of controversies. Human Relations. 25:283-306. (121)
Snadowsky, A.
1974 Member satisfaction in stable communication networks. Sociometry. 37:38-53. (128)
Trow, D. B.
1957 Autonomy and job satisfaction in task-oriented groups. J. Abnorm. Soc. Psych. 54:204-209. (51)
Walker, L. C.
1954 The effects of group size and group structure on problem-solving behavior in small groups. Unpublished Ph.D. dissertation, University of Wisconsin. (25)
Watson, D. and B. Bromberg
1965 Power, communication and position satisfaction in task-oriented groups. Journal of Personality and Social Psych. 2:859-864. (107)

Notes

1. There is, of course, an inherent ambiguity in the definition of a field, or specialty, at this point. Even the DNA literature could be seen as resting on multiple disciplines. All the scientific events in the network were coded to the extent that they belong in protein chemistry, genetics, nucleic chemistry, and microbiology. A case could be made for conducting a separate analysis within each of these disciplines making up a multidisciplinary approach to the study of DNA.

2. The differential completion times indicate differential group productivities—hence the use of *centrality and productivity* to designate this area.

3. We note, for future reference, that there has been a vast literature on centrality following the Freeman article. We think that the Freeman article provides a solid foundation for the next phase of centrality research, just as the Bavelas article did in the beginning. In principle, the centrality literature extending beyond the 1979 article can be analyzed by itself or in conjunction with the data base considered here.

4. We note that when we excluded review articles in the network, all the major findings remained unchanged.

5. This differs from the structure of the DNA network. The latter contained subgraphs that were mutually unreachable.

6. Not surprisingly, both citation networks we have examined are "near" DAGs.

7. Our results show that the centrality network is even more closely linked than the DNA network.

8. In addition to a conventional reference section, we have appended a complete list of the research productions contained in our citation data set. Some items are on both lists. Henceforth we will use the ID number in the appendix to refer to a data node in describing our results. Citations to our reference section will take the usual author and date form.

9. For each link of the main path network, there must be a corresponding link in the initial citation network. Note, however, that there is only one link out of a node in the main path network. This link is chosen by virtue of having the highest traversal count at the node. Thus, the link at article 1 in Figure 2 with the highest traversal count is to article 6. For defining main paths, nodes 2, 3, 4, and 5 are now all available as the start point for a main path from *them*. Node 2 starts another path where the first link is to node 3: this path will continue from node 3 (going to node 10), so node 3 cannot *start* a main path. Nodes 4 and 5 start main paths; however, they start paths that quickly lead to an extant main path.

10. We have omitted from Figure 2 nodes with paths that do not end with these two articles. These omitted nodes generate six more main paths, each involving one to six nodes. These residual paths represent individuals or groups who cite their own work, and that work was never cited by others in the field.

11. The split into two terminal nodes in Table 1 can be seen as a composite from Figure 2 and 3.

12. Consistent with this argument, the cross-tabulation of the identified groups by publication status is:

		Identified Group	
Publication Status	*Peripheral*	*Minor Importance*	*Crucial*
Unpublished	45%	30%	2%
Published	55%	70%	98%
Total	100%	100%	100%
	(N = 31)	(N = 30)	(N = 58)

For this table, $\chi^2(2) = 26, p = 0$. The proportion of published papers is highest for the crucial set of articles and lowest for the peripheral, as would be expected. Through time, the proportion of papers published each decade climbs steadily from 50% to 100% ($\chi^2[3] = 13.2, p = .004$). Publication counts in the determination of a main path, whereas remaining unpublished means a paper will, most likely, be irrelevant to the growth of a field.

13. In addition, the "productivity branch" of the literature may have been sustained by the energy of a single scholar.

References

Asimov, I. (1963). *The genetic code*. New York: New American Library.

Bavelas, A. (1948). A mathematical model for group structures. *Applied Anthropology, 7*, 16-30.

Bavelas, A. (1950). Communication patterns in task oriented groups. *Journal of the Acoustical Society of America, 22*, 725-730.

Bernal, J. D. (1953). *Science and industry in the nineteenth century*. London: Routledge & Kegan Paul.

Crane, D. (1972). *Invisible colleges: Diffusion of knowledge in scientific communities*. Chicago: University of Chicago Press.

Freeman, L. C. (1977). A set of measures of centrality based on betweeness. *Sociometry, 40*, 35-41.

Freeman, L. C. (1979). Centrality in social networks: 1. Conceptual clarification. *Social Networks, 1*, 215-239.

Garfield, E. (1979). *Citation indexing: Its theory and application in science, technology, and humanities*. Philadelphia: Institute for Scientific Information.

Garfield, E., Sher, I., & Torpie, R. J. (1964). *The use of citation data in writing the history of science*. Philadelphia: Institute for Scientific Information.

Hummon, N. P., & Doreian, P. (1989). Connectivity in a citation network: The development of DNA theory. *Social Networks, 11*, 39-63.

Kruskal, J. B., & Landwehr, J. M. (1983). Icicle plots: Better displays for hierarchical clustering. *American Statistician, 37*, 162-168.

Mullins, N. C. (1973). *Theories and theory groups in contemporary American sociology*. New York: Harper & Row.

Narin, F., Carpenter, M., & Berlt, N. C. (1972). Interrelationships of scientific journals. *Journal of the American Society for Information Science, 23*, 323-331.

Price, D.J.D. (1965). Networks of scientific papers. *Science, 149*, 510-515.

Small, H. G., & Griffith, B. C. (1974). The structure of scientific literature I: Identifying and graphing specialties. *Science Studies, 4*, 17-40.

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