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STRUCTURAL CONSTRAINTS ON COMMUNICATION: THE DIFFUSION OF THE HOMOMORPHIC SIGNAL ANALYSIS TECHNIQUE THROUGH SCIENTIFIC FIELDS

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Within an organizational environment there are a variety of communication channels through which information can and does diffuse. One's view about the nature of information affects which type of communication channel is expected to be most effective for diffusion. Further, each type of communication channel defines a structure within the organization. In order to determine the relative impact of various communication channels on the diffusion of information within science the diffusion of a particular method, Homomorphic Signal Analysis, is explored relative to a set of organizational structures for the relevant scientific community. Findings include the following. Methods, as information, have a map rather than a grammatical production nature. Consequently, organizational structures that combine both shared knowledge and potential for interaction are most effective in the diffusion of methods. Generalist journals and the working connections between opinion leaders play dominant roles in the diffusion of methods.

KEY WORDS: Diffusion; structure; network; innovation; information; organization.

INTRODUCTION

In 1968 Oppenheim, Schafer, and Stockham published the first paper on the method of Homomorphic Signal Analysis. In 1969 the method diffused to Geology. By 1972 the method had spread to Physics. And, by 1978 the method had spread to Social Science and Ecology. The primary question is why did the method of Homomorphic Signal Analysis diffuse in this pattern.

Diffusion, the process by which innovation spreads, is viewed as a function of the network of ties connecting the individuals in the society (Rogers, 1982). From an organizational point of view, diffusion is predictable and hence controllable, only if there are regularities in the network of ties, i.e. structures, that correlate with the pattern of diffusion. From a cognitive point of view, the nature of methods, i.e. their cognitive composition, determines which structure will best effect diffusion. From a scientific communication point of view knowing the nature of methods and which organizational structures are most effective in the diffusion process should affect the way scientists[1] choose to disseminate new ideas in the future. Further, such knowledge should aid in the design of organizational structures, hence communication channels, which enhance the dissemination of scientific methods.

To address these issues the diffusion of the method of Homomorphic Signal Analysis relative to various organizational structures in Electrical Engineering and other scientific disciplines is analyzed. Homomorphic Signal Analysis is a technique for extracting a "clean" signal given a messy signal and a model of the noise. Alan V. Oppenheim, an electrical engineer working in the area of digital signal processing, developed the method of Homomorphic Signal Analysis as part of his doctoral dissertation. Within 10 years the method had diffused within Electrical Engineering and to other scientific disciplines.

The diffusion of Homomorphic Signal Analysis is explored using a combined cognitive and network-organizational perspective. Two competing cognitive models of methods—methods as grammatical productions and methods as maps—are examined relative to a set of organizational structures for science. Given a structure it is possible to contrast the observed and expected diffusion path—see Section 4. Using comparison data it is determined which of the cognitive models is correct and which of the structures is the best predictor of diffusion—see Section 5.

1. DIFFUSION AND STRUCTURE

Diffusion research can be categorized as centered on the diffusion of technology (Coleman, et al., 1966, Anderson and Jay, 1985, Johnson, 1986, Kara-Murza, 1981, for example), or the diffusion of information (Festinger, et al., 1950, Allen, 1977, Cole and Cole, 1973, for example). This paper is in the latter tradition. The diffusion of a variety of different types of information has been studied; e.g., rumors (Festinger, et al., 1950, Festinger, 1950), job openings (Granovetter, 1974), scientific information (Price, 1965, Price, 1970), and technological information (Allen, 1977). This paper focuses on the diffusion of a specific type of scientific information—methods.

Researchers interested in diffusion are typically concerned with *when did whom adopt what* and *what is the difference between early and late adopters* (Rogers, 1982). Typically diffusion to individuals is studied (Coleman, et al., 1966, Festinger, et al., 1950, Allen, 1977, for example). Consequently, the focus is on individual's attributes; e.g., journals read (Price, 1970, Allen, 1977) and organizational position (Cole and Cole, 1973). At the organizational level differences in attributes such as size (Mansfield, 1963, Mohr, 1969), organizational slack (Cyert and March, 1963), and level of centralization and formalization (Sapolsky, 1967, Zaltman, et al., 1973) on innovation and diffusion have been studied.

Katz (1963, p. 238) noted that the "underlying assumption was always that informal communication among adopters was the key to diffusion." Informal communication is a function of personal social contact. Although diffusion may actually occur during informal communications the opportunities for such communications, at the group level, may be defined by the organizational structure. Further, from an organizational perspective, diffusion is predictable and hence controllable if the diffusion correlates with the organizational structure. Research on communication among scientists and engineers in organizations (Allen, 1977, Price, 1965, Price, 1970, Menzel, 1960) suggests that the pattern of ties between individuals, i.e. the structure, may be useful in predicting the diffusion path. Many researchers acknowledge the importance of social structure to the diffusion process (Rapoport, 1953, Katz, 1961). And yet, Rogers (1982, p. 25) notes there are relatively few studies of how the social structure affects the diffusion and adoption of innovations. A notable exception is the work on the relationship between social integration and patterns of adoption (Coleman, et al., 1966, Becker, 1970, Burt, 1973, Lin and Burt, 1975, Burt, 1980, for example).

The relationship between the topology of the social space (i.e. structure) and the spread of information (i.e. diffusion) is complex (Rogers, 1982). Researchers analyzing this relationship attempt to characterize the spread of information by various regularities or attributes of the social space; e.g. distribution of status (Cancain, 1979, Blau, 1967), strength of connections between individuals (Granovetter, 1973, Granovetter, 1974), pattern of ties in the network (Rapoport, 1953), level of network connectedness (Blau, 1977), relative size of the groups in the social space (Blau, 1977), and social position, i.e. role, (Merton, 1949, Katz and Lazarsfeld, 1955a, Ruben and Weimann, 1979, for example). Advances in network analysis have provided a conception of structure that is useful for understanding the complex relation between structure and diffusion. Social structure is conceived in terms of groups of structurally equivalent individuals (Burt, 1976, Burt, 1977, White, 1976). Multiple networks connect these individuals. Collectively, this research suggests that diffusion is the product of not one but of several structures or networks. Using this conception Burt (1980) provides insight as to why information diffuses as it does within nodes of structural equivalence. In this paper a multi-network approach is used to explain why information diffuses as it does between nodes of structural equivalence.

Nevertheless, the differential impact of various structures within an organization on the diffusion of information within the organization has not been tested. In most organizations there are multiple structures. These structures have been classified as being either informal (motivated by the individual) or formal (defined by the organization) (Crane, 1970, Katz, et al., 1963). In science one such informal structure is the set of invisible colleges (Crane, 1970). The scientific community also provides formal channels for communication; e.g., journals, conferences, scientific fields.

In the scientific arena the relationship between structure and diffusion is further complicated by the ill-defined nature of the formal structure. Within a discipline governing bodies do not *a-priori* define the relationship between sub-fields. The communication structure inherent in professional journals may be a key to the structure of science (Zhignesse and Osgood, 1967, Doreian and Fararo, 1985, Narin, et al., 1972, Carpenter and Narin, 1973). These journals, specifically the refereed jour-

[1] I use the term scientist to denote researchers who have attained a Ph.D. regardless of the area of their research. Consequently, in this data base scientists and engineers are not distinguished. Allen (1977) notes a difference in the behavior of scientists and engineers. He is, however, drawing a distinction based on years of education and not subject matter. That is, he considers scientists to have attained a Ph.D.; whereas, he considers engineers to have attained a bachelors, masters, or engineers degree.

nals, serve as a formal trading ground for ideas. The formal structure acts as both a communication and a control system (Nord, 1985, Barnlund and Harland, 1963) directing and constraining the flow of communication (Crane, 1974, Lindsey, 1978, Morgan, 1985). Hence, we might expect that methods will diffuse via the formal structures.

A basic, and usually implicit assumption, is that the diffusing information is a discrete item that can be understood in isolation. Cognitively, however, this may not be the case. The nature of information affects how information is learned (Carley, 1986a). Thus, the nature of information should affect its diffusion. Moreover, understanding the cognitive nature of information may lead to an understanding of why certain structures are more effective than others for information diffusion.

This study uses citation data for many reasons. The diffusion of Homomorphic Signal Analysis has already occurred; hence, real time data collection methods can not be used. Second, there is evidence that human recall is inaccurate; therefore, a more objective and non intrusive measure of diffusion is to be preferred. Next, the focus of this research is on diffusion to a group. In science, journal publication is indicative of diffusion to the group. Fourth, there is an assumption that the cumulative nature of science has produced a norm of citing the historical references on which the author has based his work. At the individual level, the author of the reference might not be the individual from whom the author of the new article first heard of the method. At the group level it is likely that the cited author is a member of the group from which the citing author first heard of the method. And finally, citation data has been used to look at structure of science (Doreian and Fararo, 1985, Mullins, et al., 1977, Small, 1977) and to look at diffusion of ideas in science (Cole and Cole, 1973, Gregory, 1967, Kara-Murza, 1981).

There are difficulties in using citation data. Publication delays serve to obscure the actual time at which diffusion occurs. Citations are formal statements that communication has occurred between the authors. Citations represent a formal recognition of the actual diffusion process, and an affirmation of how science is "done". Hence citation norms, such as *always cite the initial article* serve to obscure the diffusion path. Nonetheless, citation data does present the researcher with a non-invasive data source that can be used to look at not only the diffusion of information but the structure of science.

2. MODELS AND ASSUMPTIONS

This paper follows from both information processing and network analysis traditions. A multi-structure model of the scientific community is used to examine two competing models for the cognitive nature of methods. The two alternative cognitive models of methods have different implications for the communication behavior of scientists and the use of particular structures for diffusion.

2.1. Individuals, Social Structure, and Communication

Individuals are modeled as information processors—seeking, receiving, and sending information relative to a particular context or task. Individuals are connected to

other individuals by ties.[2] Collectively, these ties can be thought of as the level of comparability or substitutibility between the two individuals. The collection of individuals and the ties between them form the social network. By definition all communication occurs via the social network. When an innovation occurs information about it diffuses via the social network. Functionally diffusion occurs when transmitted information is used by the receiver. At the individual level diffusion paths are defined via the social network—see Figure 1.

A structure is a set of groups and the structural ties between these groups; hence it is a reduced mapping of the social network—see Figure 1.[3] The set of groups span the society. A structural tie exists between two groups if the number of ties between individuals in the two groups is greater than some cutoff; e.g. greater than that which might occur randomly. Two structures can differ in the types of groups and/or ties. A tie in the social network is embedded in a structure if either of the following conditions is met: 1) the two tied individuals are members of the same group in that structure, or 2) the two tied individuals are members of different groups in that structure but there is a structural tie between those groups. Whether or not a tie in the social network is used for the diffusion of a particular piece of information may be a function of the structures in which that tie is embedded.

At the group level diffusion paths are defined via the network of groups to which the information diffused—see Figure 1. Note: the diffusion path may not map onto a particular structure; i.e. there may be a diffusion tie that is not a structural tie. This can happen if there is a tie between two individuals in the social network and there is not a tie between the two individuals' groups in the structure. When the diffusion path maps onto a structure that structure determines the diffusion. For both prescriptive and descriptive reasons, it is important to determine whether certain structures are more likely to control certain types of information.

There are two types of ties that are distinguishable at both the individual and social level—interaction and knowledge (Carley, 1986a).[4] Information can diffuse between two individuals only if there is an interaction tie between them. In general, the higher the frequency of interaction the more likely it is that a particular piece of information is communicated between two individuals. Whether or not diffusion actually occurs may be a function of the nature of the information, and the relative strength of the interaction and knowledge ties. The strength of the interaction and knowledge ties may not be independent (Rogers, 1982, Carley, 1987, Burt, 1980). These points are discussed in Section 2.3.

Given the ties within an organization a set of structures can be defined. In these structures the ties between individuals are separable into formal and informal ties

[2] These ties can be built up in a variety of ways; e.g. father-son, manager-engineer, read the same journals. Over time, the strength of these ties change as changes occur in the level of interaction and shared knowledge between the individuals.

[3] Many structures may be associated with a social network depending on what groups and what ties are used to define the structure.

[4] An interaction tie exists between two individuals if the individuals have a positive propensity to interact; i.e. there are no barriers that prevent interaction from occurring. A knowledge tie exists between two individuals if they share information; i.e. they both know at least some of the same facts. The strength of the tie in the first case varies with the level of the propensity and in the second case with the level of sharing.

(Mintzberg, 1979, Mintzberg, 1983). Formal ties are work or organization related ties. By definition, formal ties between individuals embed in some organizational structure. Informal ties are non work related ties and may or may not embed in any organizational structure. It is assumed that within an organization, an individual's informal ties are distributed randomly across the other members of the organization. Assumptions about the individual's formal ties are a function of the organization being looked at.

2.2. The Scientific Environment

The scientific environment provides a context in which scientists develop and communicate information. This communication may be affected by the structure of science; i.e. the set of scientists and the ties between them. The scientific community, like any organization, can be viewed as a multistructure environment. Each structure is defined on the basis of different types of ties; discipline membership, university or college affiliation, journal read, student-teacher, and so on. Herein, three formal structures are distinguished—the formal organizational structure, the formal super-communication structure, and the functional organizational structure. There are many other structures that could have been looked at.

Structure 1, the formal organizational structure, is defined as the set of scientific fields and the organizational structural ties betweeen these fields. A scientific field can be a discipline[5] or a sub-discipline.[6] A tie exists between two fields if the fields are sufficiently substantively related; i.e. there is a high level of formal interaction and knowledge ties between the members of the two fields. It may be that the knowledge ties are stronger than the interaction ties. See Section 3.4 for operational details.

Structure 2, the formal super-communication structure, is the set of scientific fields and generalist groups and the structural ties between these groups. A generalist group is the set of individuals who read a specific generalist journal. A generalist journal serves as a central communication node for a specific scientific discipline; i.e. the majority or perhaps all of the scientists in that discipline read that journal and it is recognized and sanctioned by that discipline's society. A super-communication structural tie exists between a field or generalist group and a different generalist group if the groups are sufficiently substantively related. Unlike the formal organizational ties the strength of both the knowledge and interaction ties should be comparable. The new ties are between some group and a generalist group. See Section 3.4 for operational details.

Structure 3, the functional organizational structure, is the set of scientific fields and the ties between the knowledge gatekeepers, a.k.a. opinion leaders, in those fields. Individual scientists may work on applications in multiple fields. The network of gatekeepers is thought to be critical to the diffusion of information in science (Katz and Lazarsfeld, 1955b, Lazarsfeld, et al., 1948, Allen, 1977). Top scientists, as opinion leaders, by working in multiple fields act as functional structural ties

[5]A discipline is a generally recognized scientific area differing from other disciplines in general problem area; e.g., Chemistry, Electrical Engineering, and Economics.
[6]A sub-discipline is a recognized scientific sub-specialty within a discipline; e.g., physical chemistry, circuits, and political economics.

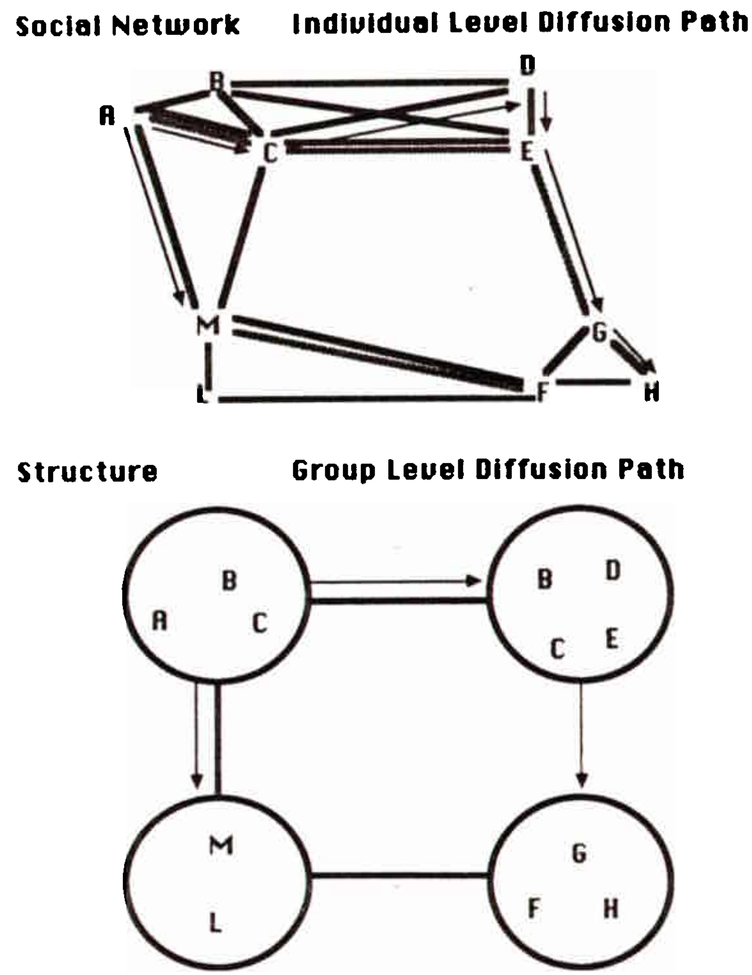


FIGURE 1. Social network, structure, and diffusion. At the top is the social network—the set of individuals and the ties between them. The letters of the alphabet represent the individuals. The lines represent the ties. If there is no line, there is no tie. Dotted lines are indicative of informal ties, and solid lines of formal ties. Person A is the innovator. The arrows show the individual level diffusion path. The information may not diffuse to all individuals, e.g., persons *l* and *f*. An individual may communicate a piece of information to many individuals (ties out of the individual node); e.g., from *A* to *C* and from *A* to *M*. There is only one individual from whom a specific individual first receives a piece of information (ties into the individual node). At the bottom is one of the possible social structures that can be formed given the social network at the top. In this structure there are 4 groups, shown as circles. Individuals can be in more than one group, e.g., *B* and *C*. But, all individuals must be in at least one group. The lines connecting the circles are the structural ties. The group level diffusion path given this structure is shown using arrows. To the extent to which the structure predicts the diffusion at the group level the group level diffusion path, derived from the individual level diffusion path, will map onto the structural ties. In this figure the group level diffusion path does not perfectly map onto the structure; note the arrow from top to bottom on the right. The non predictable diffusion happens to be the result of an informal tie between persons *e* and *g*. Whereas the predictable diffusion is the product of both formal and informal ties.

between those fields. Cross field research may increase the level of interaction and shared knowledge between fields. At any particular time, however, on average, the strength of the interaction ties formed in this fashion should be greater than the strength of the knowledge ties. See Section 3.4 for operational details.

These three formal structures can be interpreted as expectations about the individuals in the social network. All members of a group, field or generalist, are assumed to be structurally equivalent (Lorrain, 1971)[7] in formal ties *vis-a-vis* that structure.[8] These structures are assumed to be fixed *vis-a-vis* the diffusion of a particular piece of information.[9] Further, it is assumed that shared field membership represents similarity in: training, scientific knowledge, and experience. Thus field membership has a dual impact—individuals in the same field have a strong knowledge tie and a strong interaction tie. Fields are assumed to be network cliques in the level of formal ties; i.e. the intra-group formal interaction rate and the level of shared knowledge are higher than the inter-group rates. Moreover, the field members are assumed to form an invisible college (Price, 1963, Price, 1965, Price and Beaver, 1966, Crane, 1970); i.e. they have both shared paradigms (shared knowledge) and person-to-person contact.

2.3. Models of Methods

Assumptions about the nature of methods affect predictions about whether method details can be comprehended sans area of application details. A piece of scientific information may contain details on an application area and/or a method. For example, a piece of scientific information might be a discussion of a particular problem (application area details), a presentation of a specific method (method details), or a study of a particular hypothesis using a specific method (area of application and method details). Assumptions about the nature of methods actually affect predictions about which type of tie, interaction or knowledge, effects information diffusion. Further, since there are structures with fields corresponding to application areas these assumptions affect predictions about which structures will best effect information diffusion. Two alternate models for *methods* are examined: 1) methods as context free grammatical productions, and 2) methods as context sensitive maps.

2.3.1. Method as Grammatical Production

Methods can be thought of as the rules, or productions, for transforming data into information thus forming the sentences that underlie one's knowledge. In a Chomskian sense, a set of methods in association with the data form a specific type of

[7]Consequently, the expected formal interaction rate between group members is equal to the average rate of intra-group interaction. And, the expected formal interaction rate between members of different groups is equal to the average rate of inter-group interaction. Consequently, within and between groups, the expected level of shared formal knowledge is equal to the average level of shared formal knowledge.

[8]Since individuals may be in more than one group, e.g. more than one sub-discipline, by treating groups as nodes of structural equivalence, individuals who are in multiple groups are effectively being modeled as multiple individuals with ties of maximum strength.

[9]These structures may evolve as a consequence of the diffusion of that information. The dynamics of the evolution of the scientific community, however, and hence the evolution of these structures, is beyond the scope of the current paper.

grammar; one that is context free (Chomsky, 1975). As a production in a context free grammar, a method is a rule or set of rules detailing the transformation of data, such that those rules hold independent of the application area and the data's source.[10] Consequently, a method may be used to analyze data drawn from diverse sources. Methods qua productions are loosely coupled to the application area in which they evolved. Therefore, methods should be immediately transferable across application areas. Field boundaries should not systematically affect the diffusion of a method. Formal and informal ties should be equally effective *vis-a-vis* the diffusion of methods. Thus formal structures in science should not define the diffusion of the method.

Diffusion should be determined only by the strength of the interaction tie. Knowledge ties should be irrelevant to diffusion; i.e. scientists should be able to learn a method independent of the data to which it is initially applied.[11] Therefore, formal knowledge of the application area is not necessary for method comprehension.[12] Thus, the method diffusion is solely a function of interaction.

The expected rate of acceptance is dependent on the frequency of interaction between scientists. At the individual level diffusion is equally likely to occur through informal and formal interaction ties. Only tie strength affects diffusion. Given that informal interaction ties are distributed randomly relative to formal interaction ties, and that strong formal and informal ties are equally likely, then at the group level no organizational structure should determine the rate or pattern of diffusion. Diagramatically, the pattern of acceptance will look like a random walk through scientific fields—refer to Figure 2.

Ironically, under this model, the a-social nature of methods forces a situation in which all delays in diffusion are socially based. Given that methods and data are cognitively distinct, a scientist should be able to recognize the potential usefulness of a method independent of the initial application area and the scientist's research areas. Hence, diffusion delays are a function of the lack of communication channels and not the immaturity of the field or lack of appropriate data. Thus there are two reasons why a method might not be used by a field: 1) it can not be applied to that field's problems, or 2) the social topology prevents field members from learning that method. Social disconnectedness, i.e. lack of interaction ties to other scientists, inhibits method reception and use. Consequently, journals act primarily as communication mediums extending the "reach" of the communicator by effectively increasing the number of interaction ties.

The method, NMR spectroscopy, was developed in nuclear physics in order to study the magnetic resonance of atomic nuclei. Years after the initial communication

[10]One could modify the model to say that methods are context sensitive *vis-a-vis* the data. In this case the method would be a set of rules detailing the transformation of data such that those rules hold only for data with specific characteristics. The argument holds as long as the data's characteristics are not a function of the area of application.

[11]The only limitation on acquiring methods would be if a new method is an extension of an earlier method. Then it would be necessary to understand the earlier method before being able to apply the later method due to the cumulative nature of the rules within the grammar.

[12]In this model methods are cognitively distinct from data. Methods are the productions of the grammar; whereas, data are the variables. Moreover, methods are cognitively distinct and separable from social knowledge.

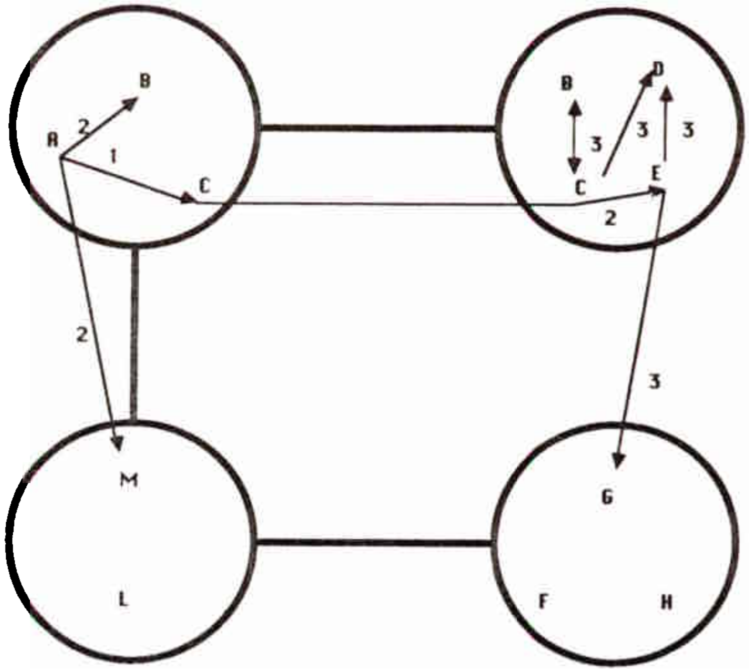


FIGURE 2. Model 1—Method as grammatical production. When methods are modeled as grammatical productions then their diffusion is dependent on the rate of interaction between individuals and not the level of shared knowledge. Hence, the informal network is of equal importance to the formal network in information diffusion. This figure shows the expected diffusion path given that methods are grammatical productions. Assume person *A* discovers the method and that at most one other person can be told of the method at a time. Then at the end of one time period the method will diffuse to the individual with whom *A* has the highest level of interaction—*C*. Then, *C* will communicate the new information to his closest associate—*E*. Meanwhile *A* will communicate the information to either *B* or *M*. And *E* will communicate the information to either *D* or *G* and so on. Note: discipline boundaries are expected to be irrelevant to the diffusion process. Further, when informal and formal interaction ties are superimposed the method is most likely to be communicated along the combined formal and informal tie due to the total interaction level being higher.

of this method it was picked up by biologists who found it useful for determining molecular structure. According to the proposed model, the delay in utilization of NMR spectroscopy by biologists would be attributed to the social disconnectedness of biologists. The model suggests that biologists form a network interaction clique such that little if any of their interaction, either formal or informal, is with scientists outside their discipline.

2.3.2. Method as Map

Alternatively, methods for analyzing data can be thought of as maps, a network of information (Carley, 1986b, Carley, 1986a). The scientist's knowledge forms a network which contains application area and method details. The scientist can only

acquire a new method if it is related to his current knowledge. Often, the innovating scientist communicates methods with application data from the initial application area. Consequently, a scientist who has knowledge of the area of application, the specific application data, or a similar method will be more likely to acquire the method than will a scientist with no such knowledge. The communication context thus affects the likelihood that the method is adopted by a particular researcher.

Methods qua maps are tightly coupled to the application area in which they evolved. The formal structures of science should determine method diffusion. Formal ties should be more effective than informal ties *vis-a-vis* the diffusion of method. Moreover, the strength of both interaction and knowledge ties should determine the diffusion of the method.

The method and the data are not cognitively distinct: both are information linked into a single network. Social knowledge also forms part of the network of facts that comprise the individual's knowledge. Knowledge of a particular scientist, or of *who knows what*, may be of equal importance to acquiring a method as knowledge of the initial application area. Informal knowledge is of little use in method communication as such knowledge relates neither to the method nor the initial application area. Frequency of informal interaction, where it decreases formal interaction, will inhibit method communication.

If the method is tightly coupled to the application then the acceptance rate is dependent on the level of shared knowledge and the frequency of interaction. Assuming that informal ties are distributed randomly relative to the formal topology and that individuals with formal ties have similar training, experience, and knowledge *vis-a-vis* the pursuit of science then it is expected that the impact of informal interaction between individuals is minimized. Since the formal topology combines shared knowledge and interaction, field boundaries should act as barriers to communication, and ties between fields should act as channels enhancing communication.

Big time gaps should occur as a method passes between disciplines due to the lack of shared knowledge. Otherwise, similarity in the fields' application area will determine the pattern and rate of acceptance. The rate of method diffusion between fields is dependent on the structural ties. Holding all else constant, during a single time step the method is picked up only by related fields, as in Figure 3.

Transmission errors occur due to distance in both the interaction and knowledge network. Since interaction leads to shared knowledge, formal interaction leads to shared formal knowledge. Consequently, social disconnectedness at the formal level is sufficient to inhibit method communication. Moreover, unlike model 1, it can no longer be assumed that scientists always recognize the potential usefulness of a method. It is still assumed that such a failure is not based on the immaturity of the field. Rather, failure to recognize the potential usefulness of a method is due to context overload. Context overload is a type of transmission error that occurs when a signal carrying information on the method and the initial application area can not be decoupled into the component signals. Context overload can cause the methods not to be picked up by all fields where it might prove useful. If context overload occurs, only fields closely related to the source field will pick up the signal carrying

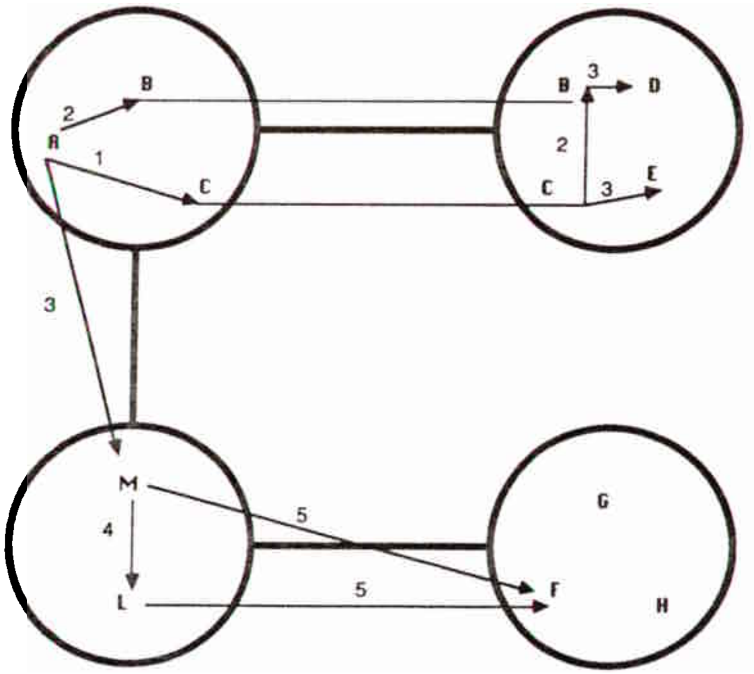


FIGURE 3. Model 2—Method as map. When methods are modeled as maps their diffusion is dependent on the formal network. It is not sufficient that individuals have a high level of interaction, they must also have a high level of shared knowledge *vis-a-vis* the method or application area being communicated. This figure portrays the expected diffusion given that methods are maps. Person *A* discovers the method. First the method will diffuse to *C*. Then *C* will communicate the method to *B*, who will communicate it to *D*. At the same time *A* tries to communicate the method to *B*. Next *C* will tell *E*. Note: in this case diffusion is expected to follow the formal network and to be constrained by formal group boundaries.

the method. Journals act as control mechanisms maintaining group boundaries by setting context.

Under this model context overload is the most likely reason that biologists delayed acceptance of NMR spectroscopy. That is, at the formal level biologists and nuclear physicists are sufficiently disconnected in interaction and/or knowledge that they can not understand each other. The model would suggest that there are several possible causes for the observed delay; the groups are socially disconnected, the groups are cognitively disconnected, or there is context overload. Both interaction and formal knowledge ties are necessary for diffusion. Whereas, the amount of information in the message simply affects the difficulty of the transaction. If there are interaction ties between the two groups, then it is the lack of shared knowledge that inhibits method diffusion. In this case, the adopter and the sender do not have sufficient levels of shared knowledge about the area of application to be able to "understand" the same article.

2.3.3. Contrasting Hypotheses

Model 1—method as grammatical production—and model 2—method as map—differ in the following fashion. Under model 1 lags in adoption can only occur if the adopter and the sender are socially disconnected, i.e. they do not interact. Under model 2 social disconnectedness, cognitive disconnectedness, or context overload can cause adoption delays. Under both models interaction ties are necessary to diffusion. Under model 1, but not model 2, method details can be comprehended sans area of application details. Which field first picks up a method is dependent on: in model 1 the density of interaction ties between the two groups, and in model 2 the density of interaction and formal knowledge ties. Which individual first picks up a method is dependent on: in model 1 the scientist's social position, and in model 2 the scientist's social position and current knowledge.

A limitation of both models is the assumption that all fields are at a stage of development where if they can ever use the method they can do so at the current time. Since it is really individual scientists who adopt methods this suggests that there is always some scientist within the field who is capable of adopting the method. Delays in method acceptance are attributable to lack of receipt and not inability to make use of, or lack of an appropriate problem, at the time of innovation.[13]

3. DATA COLLECTION AND CODING

Data for this study is drawn from several sources: the Science Citation Index, the society list for the Institute of Electrical and Electronic Engineers (IEEE), the National Science Foundation (NSF) organizational chart, departmental listing for several major universities, a questionnaire administered to Electrical Engineers at Berkeley, CMU, MIT, and Stanford, and a discussion with Professor Oppenheim. Data from the Science Citation Index is used to assess group acceptance and intergroup ties. The final list of sub-disciplines is derived from the NSF organizational charter and the departmental listings. The questionnaire is used to determine ties in the functional organizational structure in Electrical Engineering. And the discussion with Oppenheim aided in the interpretation of the results.

Two research considerations affect the kind and amount of data collected. First, since the research focus is to determine whether or not there are structural effects on method diffusion group level data is needed. Second, since the focus is on which group got the method when and from whom, and not with explaining why a particular group never used the method it is not necessary to enumerate all possible groups; rather it is sufficient to list those groups to which the method did diffuse. It is neeessary to enumerate all structural ties between the groups to whom the method did diffuse.

[13]This paper is not concerned with the cognitive capabilities of a particular individual: this paper is not concerned with whether a particular researcher understands and uses a particular method. Individual cognitive differences in the ability to grasp and understand a new method are treated as effectively random relative to structural effects.

3.1. Citation Data

Citation data is used to determine the list of journals in which the method of Homomorphic Signal Analysis is used or referred to. This information is necessary for setting boundaries on the group list and constructing the group level diffusion path. Citation data was gathered by using the science citation index to trace first order and second order citations of the originating article. For each citation the following information is kept; id, authors last name and first initial, journal,[14] title, year, id of article cited, and citation order.[15] The originating article is *Nonlinear Filtering of Multiple Convolved Signals* by Oppenheim, Schafer, and Stockham in the Proceedings of the IEEE, 1968. First order citations are citations to the originating article. Second order citations are citations to first order citations.[16]

I gathered citation data for a ten year time span—1968 to 1978. According to the Science Citation Index 73.2% of the projected number of citations to an article published in the sciences in 1968 have occurred by 1979 (SCI-7-79, 1980, p. 28). This study is concerned with initial adoption of a method by a field and not the lifetime of a publication. Given these two facts a ten year time span seemed sufficient.

Within a particular publication there may be both first and second order citations. The data base includes all such citations. In this analysis publications are coded by year of publication and not year of occurrence in the Science Citation Index. Each year is treated as a separate time period.

The resulting data base contains 1042 citations: 105[17] are first order and 937 are second order.[18]

Four types of citations were extracted from the data base prior to constructing the group level diffusion path. First, all citations in articles published in foreign journals are extracted. This eliminated potential difficulties due to different cultures having, perhaps different ways of defining fields and denoting field boundaries within science. Second, all citations in articles published in general scientific magazines or journals are extracted. This eliminated the need to define on an article by article basis the appropriate field for that article. It was also assumed that publications in such journals contained more general information about the author's field and fewer details on the method *per se'*. Third, all citations occurring in books are extracted. This eliminated the problem of correctly classifying the book by field. It was also assumed that the amount of information in the book is so high that little of it actually pertained to the method; therefore, citations to the book could not be guaranteed

[14]If the reference occurred in a book and not a journal, the term "BOOK" appears here.

[15]Since citations are characterized by author, journal, and year there is a possibility of under-counting the actual number of references. Two articles by the same author in the same year in the same journal are treated as a single citation. Although this possibility exists it is irrelevant to the current study as the focus is on the movement between fields and not the extent of specific references.

[16]The underlying assumption is that if a method is new to a field articles in which the method is used must justify this use by referring to other works that use this method. Under this assumption an alternate measure of the acceptance of a method by a field might be the number of articles in which that method is used in which there are no references to other works that define the use of alternate methods. A problem with using citation to denote usage is that the further the citation is from the publication in which the method was initially defined the less likely that the citing work actually deals with the method. Since, this analysis uses only first and second order citations this problem is mitigated.

[17]This includes the initial article as a citation to itself.

[18]The data base is available on request.

to be citing the book because of its description of the method. Note: none of the books dealt exclusively with detailing the method. And fourth, all citations to the extracted publications are extracted. This eliminated the possibility of there being second order citations that are not linked to any group, and so appeared to get the method from nowhere. After this elimination process there remained 842 citations (90 first order and 752 second order) by 452 unique authors in 121 unique journals 96 of which are not IEEE journals.

3.2. Matching Groups and Journals

Since the impact of organizational structures on diffusion is being studied using citation data it is necessary to map specific journals to specific groups. In order to do this, the set of groups to which the method of Homomorphic Signal Analysis had diffused are located. The first step in locating the set of groups is to determine the level of granularity at which to define fields. Of the 842 citations 459 (55%) occurred in IEEE journals, and 629 (75%) are in journals associated with Electrical and Computer engineering. Based on the prevalence of journals associated with Institute of Electrical and Electronic Engineers and the fact that the method was developed in the area of Electrical Engineering it was decided to utilize sub-discipline boundaries within Electrical Engineering and discipline boundaries outside of Electrical Engineering. Given this decision, the only generalist journals that are identifiable as separate from a field are those associated with Electrical Engineering. The second step in locating groups was to establish criteria for defining fields. Three different criteria were used, one for each type of field: sub-disciplines, generalist, and disciplines. For a list of fields refer to Appendix 1.

Fields which are sub-disciplines—There must be an associated IEEE society. The IEEE lists 35 recognized societies. These are the recognized sub-disciplines of Electrical Engineering and not necessarily the sub-disciplines identified by practitioners. For example, the list does not contain VLSI or CAD which are sub-disciplines identified by practitioners.[19] And, the IEEE list contains sub-disciplines which are not typically considered as working research sub-disciplines by the practitioners such as *E—Education*, *EMC—Electro-Magnetic Compatibility*, and *IA—Industrial Applications*. Associated with each of these sub-disciplines is a recognized IEEE refereed journal and sometimes a general magazine. The IEEE has 49 distinct publications, one each for the 35 sub-disciplines, two generalist journals, and 12 magazines and industrial publications. Each of the 12 magazines is associated with one of the 35 sub-disciplines.[20] Using this criteria 35 fields are identified.

Fields which are generalist—There must be an associated IEEE generalist journal. The IEEE publishes two generalist journals—*Proceedings of the IEEE* and *IEEE*

[19]In a questionnaire administered to Electrical Engineers at MIT, CMU, Berkeley, and Stanford *VLSI—Very Large Scale Integration* and *CAD—Computer Aided Design* were among the sub-disciplines not recognized by the IEEE that were the most frequently mentioned by the engineers who completed the questionnaire.

[20]Which of the 35 area journals and 12 magazines an Electrical Engineer receives depends on his society membership.

Spectrum. All members of the IEEE receive the two generalist publications. Using this criteria 2 fields are identified.

Fields which are disciplines—Other than Electrical Engineering, the field must occur either in the NSF organizational charter or have departments associated with it at several major universities. Using this criteria 40 fields are identified.

The third step in locating groups is to determine to which of the possible groups the method of Homomorphic Signal Analysis had actually diffused. This is done by comparing the title of the journal with the title of fields that could be identified using the three criteria stated above. The 842 citations are in publications that occurred in 121 unique journals, 25 of which are IEEE journals. The unique journals are used to select which of the possible fields that could be identified using the three previously cited criteria are fields to which the method of Homomorphic Signal Analysis actually diffused. Of the 25 IEEE journals, 23 are associated with a specific IEEE recognized society and the remaining 2 are the generalist journals. For the 96 non IEEE journals, on the basis of journal title 37 are identified as being related in content area to IEEE recognized societies. The remaining 59 journals are mapped onto the non Electrical Engineering fields. A set of 21 disciplines (not including Electrical Engineering) are identified. As a result of this identification process 46 fields were enumerated: 23 IEEE sub-disciplines, 2 generalist groups, and 21 disciplines.

3.3. Locating Structural Ties

Two methods are used to measure structural ties—cross-journal citation rates and co-membership of an opinion leader.

Cross-journal citation rates indicate the degree of formalized interaction and shared knowledge within and between fields.[21] High cross citation rates betweeen journals suggest both strong formal knowledge and interaction ties between the associated fields. Cross-journal citation ties exist between two groups if there are at least five citations between the groups and at least 5% of the citations of one of the groups is to the other group.[22] In calculating the 5% level, citations in all journals associated with the groups are used. For IEEE sub-disciplines a tie was placed provided that at least one of the two sub-disciplines had a cited or citing rate to the other sub-discipline greater than or equal to 5%. To locate the ties from Electrical Engineering to other disciplines only the citing data is used. Thus, if the total number of cites from all journals in a non Electrical Engineering field to a field in Electrical Engineering was greater than 5% of the cites to the latter a link is placed between those fields.[23] Only citing data is used as the concern is with how information flows out of Electrical Engineering.

Co-membership ties are based on sample data drawn from the questionnaire administered to researchers at Berkeley, CMU, Stanford, and MIT. As these are the top 4 schools in Electrical Engineering, researchers at these schools are assumed to be discipline opinion leaders. The relevant question simply asked the scientists to list the sub-disciplines in which they worked based on a list of fields. The list of fields included all of those sub-disciplines listed by the IEEE. A scientist is a co-member of two groups if he denoted that he worked in both fields.

3.4. Organizational Structures

Three structures were identified—the formal organizational structure, the formal super-communication structure, and the functional organizational structure. Each structure is defined as a set of groups and the ties between the groups.

Formal Organizational Structure—The groups are the 23 IEEE sub-disciplines and 21 disciplines (not including Electrical Engineering) previously identified. A tie was placed between two groups provided there was a 5% cross-journal citation rate between the journals associated with the fields. All fields are tied to themselves. In addition, a tie is placed between two non-IEEE fields provided the subject matter of those sciences are directly related. There are 76 ties in this structure.

Formal Super-communication Structure—The groups are the 23 IEEE sub-disciplines, 21 disciplines, and the 2 generalist groups. The set of ties includes all ties in the formal organizational structure plus the ties to and from the generalist groups. Since all members of the IEEE receive *Spectrum* and *Proceedings* a link is placed between the generalist groups and all 23 IEEE sub-disciplines. Based on a 5% citing rate, there is also a tie from *Physics* to the *Proceedings*. There are 148 ties in this structure.

Functional Organizational Structure—The groups are the 23 IEEE sub-disciplines. A tie exists between two groups if there is an opinion leader who works in both sub-disciplines. This structure can be thought of as the functional or research structure for Electrical Engineering. This structure has 246 ties.

3.5. Group Level Diffusion Path

A method is considered to first reach a field when the first article in a journal associated with that field appears that cites a previous work which used or defined the use of that method.[24] This definition is based on the following three assumptions:

[21] Cross-journal citation rates are used to establish ties rather than co-citation analysis as the goal is to discern the structure of an area of science and not a speciality within a particular sub-discipline. Co-citation analysis has been used to represent the structure inherent within the literature *vis-a-vis* a particular speciality (Small and Griffith, 1974). Unless the authors are members of an invisible college then the co-citation matrix may not be representative of the group (Noma, 1984); consequently, the derived structure may not be the "true" structure. Since the authors of the articles in question can not be considered members of an invisible college deriving the structure through co-citation analysis would be inappropriate.

[22] Cross-journal citation rates were first published for the physical sciences and engineering in the Science Citation Index in 1979. The Science Citation Index lists both citing and cited rates and the number of cross-journal citations for major journals in science and engineering to the most commonly citing/cited journals.

[23] Since the Science Citation Index only lists the most frequently citing journals this measure would tend to be lower than the actual cross-discipline citation level. Consequently, the model may contain fewer links than it would if full data were available.

[24] This only covers the passage of innovative methods and not the development of new methods. Cycles in citations do exist. A cycle occurs if individuals in field *A* cite work in field *B* at time (*t*), and then at time ($t + n$), individuals in field *B* cite work in field *A*. Such cycles may affect the rate at which the acceptance level increases; but, they do not affect the initial diffusion path.

publication indicates membership,[25] citation indicates usage,[26] and publication indicates acceptance.[27] The observed diffusion path is thus defined in terms of citations.

The observed diffusion path must be measured relative to the structure being analyzed, i.e. the same groups must be used. Therefore, since there are three structures three diffusion paths are needed—HSA1, HSA2, and HSA3. HSA1, 2, and 3 are data bases containing citation data for Homomorphic Signal Analysis based on the general citation data base with 842 citations. They differ in which groups there are citations to and from.

HSA1—contains only citations that are to and from groups in the formal organizational structure. HSA1 contains 360 citations in 70 unique journals, 51 of which are not IEEE journals. The corresponding articles were written by 206 authors working in 31 different fields. Of these 360 citations 197 are interfield cites, and 163 are intra-field cites.

HSA2—contains only citations that are to and from groups in the formal super-communication structure. HSA22 contains all 842 citations: 632 inter-field cites and 210 intra-field cites.

HSA3—contains only citations that are to and from groups in the functional organizational structure. HSA3 contains 208 citations: 100 inter-field cites and 108 intra-field cites.

4. METHOD OF ANALYSIS

The observed and expected diffusion paths are contrasted. The observed diffusion path is the set of citations between groups in the structure. The expected diffusion path depends on the structure. These paths are contrasted by mapping the observed path onto the structure and counting the number of citations that correspond to ties in the structure.[28] This mapping allows the determination of which cognitive model of methods is correct. Recall that in the first two structures there are ties just in case the average rate of inter-journal citation is high. And, in the third structure there are ties just in case an opinion leader works in both fields. An inter-journal citation where the average rate of inter-journal citation is high is an affirmation of the usefulness of formal interaction and shared knowledge ties. Whereas, a low rate is an affirmation of the usefulness of informal interaction ties and a disaffirmation of the usefulness of formal knowledge ties. Similarly, an inter-journal citation where there is an opinion leader is an affirmation of the usefulness of informal interaction ties and formal knowledge ties. Whereas, a citation and no opinion leader is an affirmation of the usefulness of informal interaction ties and a disaffirmation of the usefulness of formal knowledge ties. Consequently, the better the mapping between the structure and the observed diffusion path the more likely it is that model 2, method as map, is correct. Moreover, if model 2 is correct then more of the ties in the first two structures which are based on cross-journal citation rates should be utilized for diffusion than are ties in the third structure which is based on co-membership of opinion leaders.

The following calculations (see Figure 4) are made for three levels of citations—total,[29] unique,[30] and initial[31]—both for all fields, and for just IEEE fields. Since the concern is with diffusion between fields, and not within fields, only inter-field citation data is utilized.

Ascribed diffusion matches and misses—the number of citations that match and do not match the structure. This is not a time based measure; rather, it simply measures the degree of similarity in the pattern of the observed and expected diffusion paths. If there is a tie between two citation paths then the preference is given to the citation that corresponds to the structure. If the ratio of matches to non matches is greater than 1 then model 2 (method as map) has more predictive power; whereas, if the ratio is less than 1 then model 1 (method as grammatical production) has more predictive power.

Lag data—the number of citations that occur early, late, or on time relative to the model for both a lag of one year and two years.[32] Since it is not clear what the appropriate time step for communication is a lag of both one and two years are examined. Early citations indicate that model 1 is correct; whereas on time citations indicate that model 2 is correct. A high number of late citations is a weakly suggestive of model 1. Early citations are clear indicators that the formal structure

[25] When an article is published in a journal associated with a particular field the author is considered to be a member of that field.

[26] If a paper is published which cites an article which defines the use of a method then the citing authors are said to use that method. While citation may indicate method utilization it does not guarantee it. Since the concern is with initial method acceptance and not method utilization after acceptance a citation indicator of usage is felt to be sufficient.

[27] The appearance of an article that involves a method in a field's journal constitutes method acceptance by at least some of the field researchers. This claim can be made as only refereed journals are used for this analysis. Publication of a method in a refereed journal requires at least some other researchers in that field to either accept the method or to find it to be potentially acceptable. As more articles making use of the method appear in the field's journals the degree of acceptance of that method by field members is increasing.

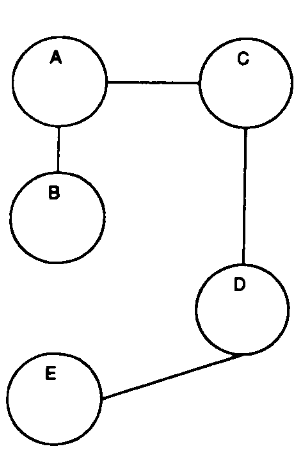
[28] A program was written in C under UNIX which contrasts the observed and expected diffusion paths. C is a high level structured programming language—(Kernighan, 1978). UNIX is a general computer operating system written in C—(Kernighan, 1984). This program takes two inputs—the data base with the citation data and the data base with the structure. It then forms the observed and expected diffusion paths. The program then calculates various measures of similarity in the two paths.

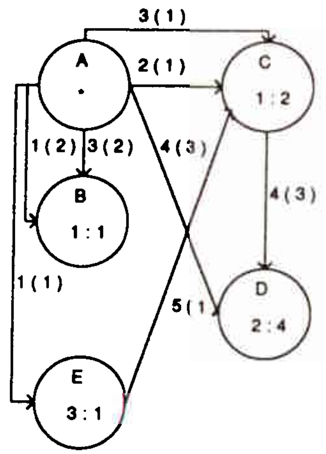
[29] All inter-field citations are total. The calculations based on the total set of citations measure the degree to which all citations match the structure. These calculations are the weakest test of model 1 and the strongest test of the model 2.

[30] Unique inter-field citations are determined in a journal independent fashion and only the first, i.e. oldest, citation is kept. The calculations based on the unique set of citations measure the degree to which the complete diffusion path can be predicted using the structure. These are a strong test of model 1 and a weak test of model 2.

[31] Initial adoption inter-field citations are measured as the time at which that field first cited another field in the data set. Initial citations are determined in a journal independent fashion. The number of initial citations will equal the number of fields minus one (for the originating field) as each field will have at most one inter-field citation that originates in that field. The calculations based on the initial a citations measure the degree to which the initial diffusion path is predicted by the model. These are a strong test of model 1 and a weak test of model 2.

[32] A lag of one year means that the connected fields are expected to be about one year apart in terms of when they use the method. In this case if fields *A* and *B* are connected an article using a new method is published in field *A* in 1973 then by 1974 it is expected that an article using that method will occur in field *B*. Whereas, a lag of 2 years would suggest that an article using that method would be published in field *B* in 1975. The delay in publication in the IEEE tends to range from 9 months to 1 and 1/2 years.





DATA ANALYSIS

	TOTAL	ALL FIELDS UNIQUE	INITIAL	FIELDS
Total	14	6	4	NA
ASCRIBED DIFFUSION				
Matches	9	3	3	NA
Misses	5	3	1	NA
LAG 1				
Early	1	1	1	1
On Time	2	1	1	1
Late	11	4	3	2
LAG 2				
Early	3	2	2	2
On Time	8	4	3	2
Late	3	0	0	0
DISTANCE METRIC				
Matches	14	6	4	NA
Misses	0	0	0	NA

FIGURE 4. Example of how to measure diffusion. In this example, the structure of the scientific community (left), is composed of 5 fields (circles) and 4 ties (lines). All ties in the model are bi-directional. The observed citation path is on the right. In this example the method diffuses to all 5 fields (circles) via 14 ties, i.e. citations, (arrows), 6 of which are unique field to field ties, and 4 of which represent initial acceptance. Field *A* is the field in which the method originated. The first number in the circle indicates the year of expected acceptance given a lag of 1 and the second number indicates the year of actual acceptance. Note: all ties are uni-directional. The arrow points in the direction of information flow and is annotated with the year in which the citation occurred and the number of such citations. For example, consider the arrow from field *A* to field *B* labeled 1(2). This arrow indicates that in the first year after publication there were 2 articles in field *B* that cited a work in field *A* that used the method. At the bottom is a printout of the statistics calculated when contrasting this model and data.

is not being used. Whereas, late citations may be attributable to a variety of causes other than that the method is not diffusing through the structure such as extensive publication delays.

Distance metric matches and misses—the number of citations that are correct relative to the possible paths in the structure. There exists a possible path between two fields if based on the ties in the structure there is a path between those fields that is less than or equal to the maximum time span being looked at. This measure indicates if it is possible for the method to be transferred between the corresponding fields along structural ties in the amount of time that it actually took for it to diffuse. If field *G* cites field *A* and there is not a path in the structure connecting these fields then the existence of the citation is indicative of model 1 (method as grammatical production). If the ratio of correct to incorrect citations is greater than 1 then model 2 (method as map) has more predictive power; whereas, if the ratio is less than 1 then model 1 (methods as grammatical productions) has more predictive power. If there is a possible path then information could have flowed that way despite the lack of citations. If there is not a possible path and yet there is a citation then it is not possible for the communication to be due to the formal structure. Consequently, this is a stronger measure for model 1 than for model 2.

5. THE DIFFUSION OF HOMOMORPHIC SIGNAL ANALYSIS

In 1968 Alan V. Oppenheim published a paper in the Proceedings of the IEEE entitled "Nonlinear Filtering of Multiplied and Convolved Signals" with Ronald W. Schafer and Thomas G. Stockham Jr. While not the very first manuscript ever written in the field, it was to be the definitive work in that it formulated a general method for nonlinear filtering of signals which have been combined by multiplication or convolution. This was a generalization of an earlier technique developed by Bogert, Healy, and Tukey (1963) called Cepstral analysis. Cepstral analysis is a technique for filtering convolved signals which are minimum phase.[33] The original authors, Oppenheim, Schafer, and Stockham, do research in the sub-discipline of acoustic, speech, and signal processing (ASSP). Their original ideas for applications lay in the area of image and audio processing; e.g. restoration of vintage records and increasing the contrast in photographs. The method of homomorphic signal analysis was to be used in fields far from the original and to have applications never dreamed of by the authors.

By the end of 1978 there were 105 citations to the original article—refer to Figure 5. These articles were by 87 different authors, published in 51 different journals, and associated with 27 different subdisciplines or disciplines. By 1978 the number of citations appear to begin to taper off. The work, however, is still being cited.

The general method of homomorphic signal analysis began as Oppenheim's Sc.D. thesis at MIT. Stockham was a reader for this thesis. Oppenheim then joined the faculty at MIT in Electrical Engineering. His first doctoral student was Schafer. The three authors formed a tight knit group which jointly and independently published

[33]This technique is analogous to normal spectral analysis on linear systems. To indicate this the authors have convoluted the words spectral, filtering, analysis, frequency, and phase to form the humorous analogs cepstral, liftering, alanysis, quefrency, and saphe.

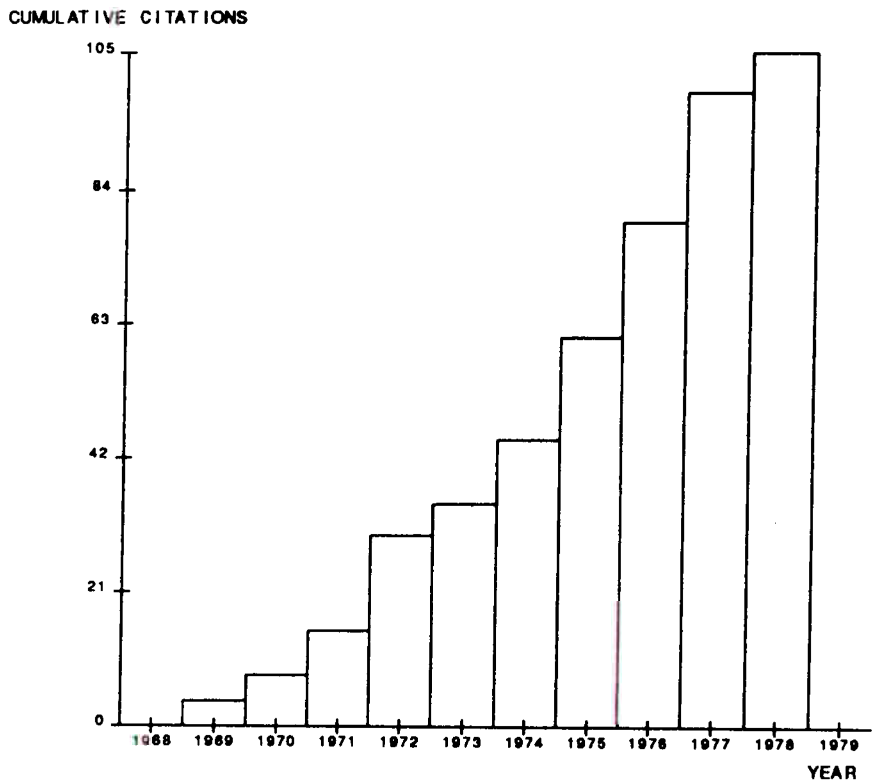


FIGURE 5. Cumulative first order citations. By 1978 the rate of increase for first order citations appears to be slowing down. Although, the initial article is still heavily cited.

many papers on homomorphic signal analysis, 8 in this data set alone (not counting the original article). As Oppenheim pointed out, at first the research involving Homomorphic Signal Analysis was 'quite contained', only the three of them were interested. In 1969 there are only 4 cites to the original article: one by Oppenheim in ASSP, one in *Science*,[34] one in *Spectrum*, and one in Geology. And, it was not until 1970, two years after the original article was published, that the method had penetrated to other sub-disciplines in IEEE.

Each year the method of Homomorphic Signal Analysis spread to new fields—refer to Figure 6. The peak year for initial field acceptance was 1972 when 11 new fields picked up the method. By 1973 96% of the fields in IEEE that were to pick up the method in the first 10 years had. Whereas, 43% of the non IEEE fields that were to pick up the method did so after 1973. Thus, at the gross level there is a discipline impact. This is weak support for model 2, method as map.

[34]Note: this cite is not included in the data sets analyzed as it is in a general scientific journals.

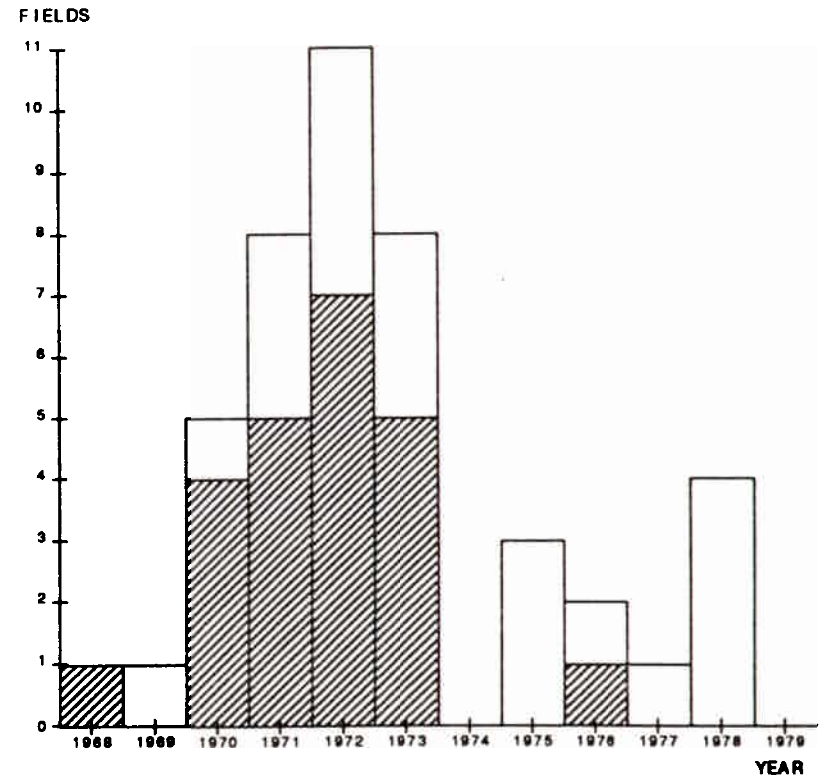


FIGURE 6. Fields by year. This figure shows the number of new fields that adopted Homomorphic Signal Analysis by year. Note that 1972 is the peak year with 11 new fields. The bottom part of each column, the shaded part, indicates the number of IEEE sub-disciplines, and the top half the number of non-IEEE fields. By 1973 22 of the 23 sub-disciplines in IEEE that were to exhibit initial acceptance in the first 10 years had.

5.1. Impact of Formal Organizational Structure

The formal organizational structure (Figure 7) shows a fairly low level of interconnectedness between the fields.[35] Most sub-disciplines in Electrical Engineering are connected to only one other sub-discipline, and only 5 sub-disciplines in Electrical Engineering are connected to 2 or more sub-disciplines in Electrical Engineering.

[35]Note: this structure contains only those fields to which the method of Homomorphic Signal Analysis actually diffused in the first 10 years. Consequently, the actual level of connectedness, if all fields had been included, would have been a little higher than that shown in this picture. For simplicity of presentation, all four networks for the spread of Homomorphic Signal Analysis—Figures 7–10—are shown with the same set of fields. This set of fields includes only those fields to which the method actually diffused by 1978. Figures 9 and 10 also include the two generalist journals *IEEE Spectrum* and *Proceedings of the IEEE*.

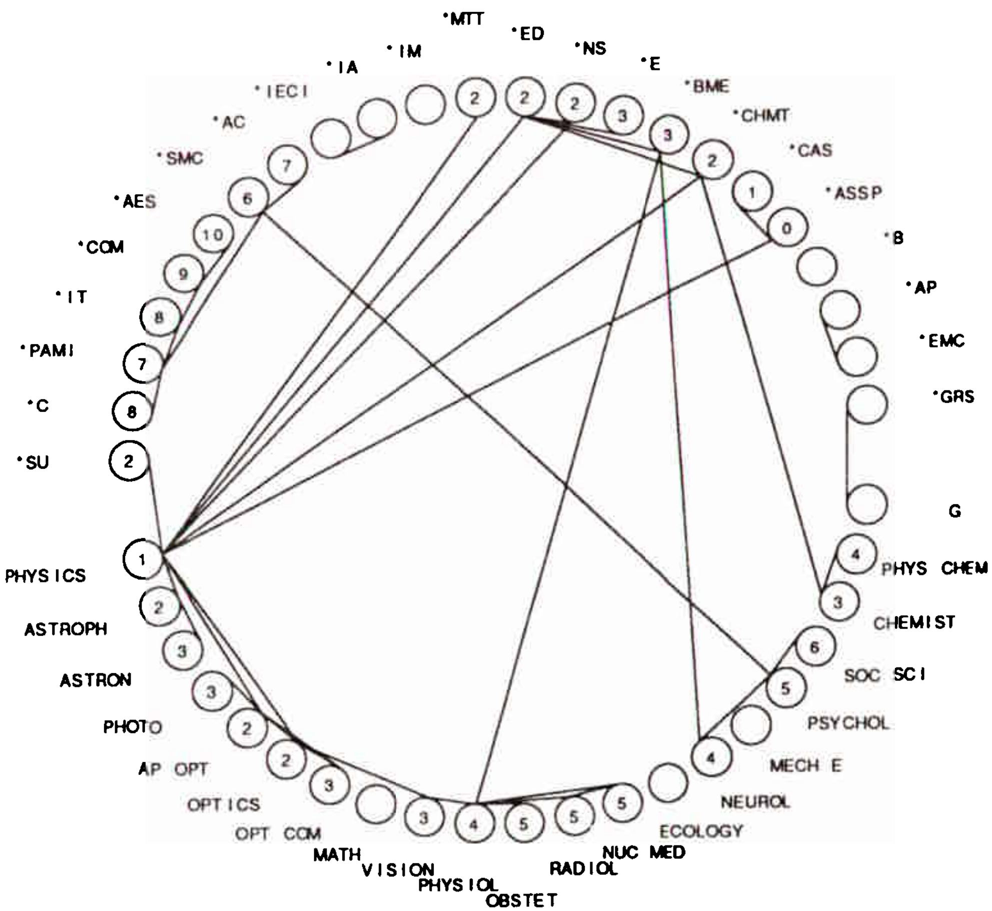


FIGURE 7. Formal organizational structure. This figure shows the formal organizational structure. Each circle represents one of the 44 formal fields. Each line indicates that the connected fields have a cross citation rate of at least 5%. The number in each circle indicates the minimum number of steps that the field is from the initiating field, *ASSP—Acoustics, Speech, and Signal Processing*. Only 4 of the fields are disconnected from all others: *IM—Instrumentation and Measurement, B—Broadcast, Cable and Consumer Electronics, MATH*, and *ECOLOGY*.

This pattern suggests that the sub-disciplines of Electrical Engineering are distinct with fairly non-overlapping application areas. The most common tie to non-IEEE disciplines is to PHYSICS (6 ties); thus, giving social credence to the historical fact that for many of the devices in Electrical Engineering the underlying principles were discovered in *PHYSICS*. There are only 5 ties between IEEE sub-disciplines and the non-IEEE fields that are not to *PHYSICS*. Since the method of Homomorphic Signal Analysis was developed in the field of *ASSP—Acoustics, Speech, and Signal*

TABLE 1
Diffusion via the Formal Organizational Structure—HSA1

	All Fields				Only IEEE			
	Total	Unique	Initial	Field	Total	Unique	Initial	Field
Totals	197	76	38	46	100	35	18	23
Ascribed Diffusion								
Matches	45(22.8)	17(22.4)	6(15.8)	NA	13(13.0)	7(20.0)	3(16.7)	
Misses	152(77.2)	59(77.6)	32(84.2)	NA	87(87.0)	28(80.0)	15(83.3)	NA
Lag 1								
Early	28(14.2)	24(31.6)	15(39.5)	21(45.7)	13(13.0)	10(28.6)	6(33.3)	8(34.8)
On Time	9(4.6)	6(7.9)	4(10.5)	4(8.7)	3(3.0)	2(5.7)	1(5.6)	2(8.7)
Late	160(81.2)	44(57.9)	19(50.0)	21(45.7)	84(84.0)	21(60.0)	11(61.1)	1(56.5)
Lag 2								
Early	85(43.2)	45(599.2)	26(68.4)	30(65.2)	47(47.0)	20(57.1)	12(66.7)	14(60.9)
On Time	18(9.1)	8(10.5)	3(7.9)	5(10.9)	8(8.0)	2(5.7)	1(5.6)	3(13.0)
Late	94(47.7)	21(27.6)	9(23.7)	11(23.9)	45(45.0)	11(31.4)	5(27.8)	6(26.1)
Distance Metric								
Matches	192(97.5)	72(94.7)	34(89.5)	NA	98(98.0)	33(94.3)	16(88.9)	NA
Misses	5(2.5)	4(5.3)	4(10.5)	NA	2(2.0)	2(5.7)	2(11.1)	NA

Processing if model 2, method as map, is correct then given the formal organizational structure the first fields to adopt the method should be *CAS—Circuits and Systems*, and *PHYSICS*; whereas, *ECOLOGY*, for example, is not expected to adopt the method.

Figure 8 portrays the observed initial diffusion of the method Homomorphic Signal Analysis. The first field to pick up this method is *G—Geology* in 1969. The next year both *C—Computer and AP OPP-Applied Optics* picked up the method. Expected first adopters were late; *CAS—Circuits and Systems* 1973 and *PHYSICS* 1974. Given the formal organizational structure, model 2, method as map, does not appear to be a good predictor of the timing of the actual diffusion path.

The data in Table 1 confirm that given the formal organizational structure model 2, method as map, is a poor predictor of the actual diffusion path. Only 45 of the 197 total citations, 17 of the 76 unique citations, and 6 of the 38 initial citations are correctly predicted by model 2. With a lag of one year only 3 fields accepted the method on time and 8 fields had early acceptance. With a lag of two years only 4 fields accepted the method on time and 17 fields had early acceptance. Both sets of measures seem to suggest that model 1 has more explanatory power than does model 2. In Table 1 it can be seen that 192 (97.5%) of the total citations, 72 (94.7%) of the unique citations, and 34 (89.5%) of the initial citations could be the end product of information flowing via structural ties (distance metric). This mixed support suggests that the formal organizational structure determines the diffusion pattern but not the rate. This is to be expected if factors such as publication delays and citation norms dominate the rate of diffusion when measured via citation data.

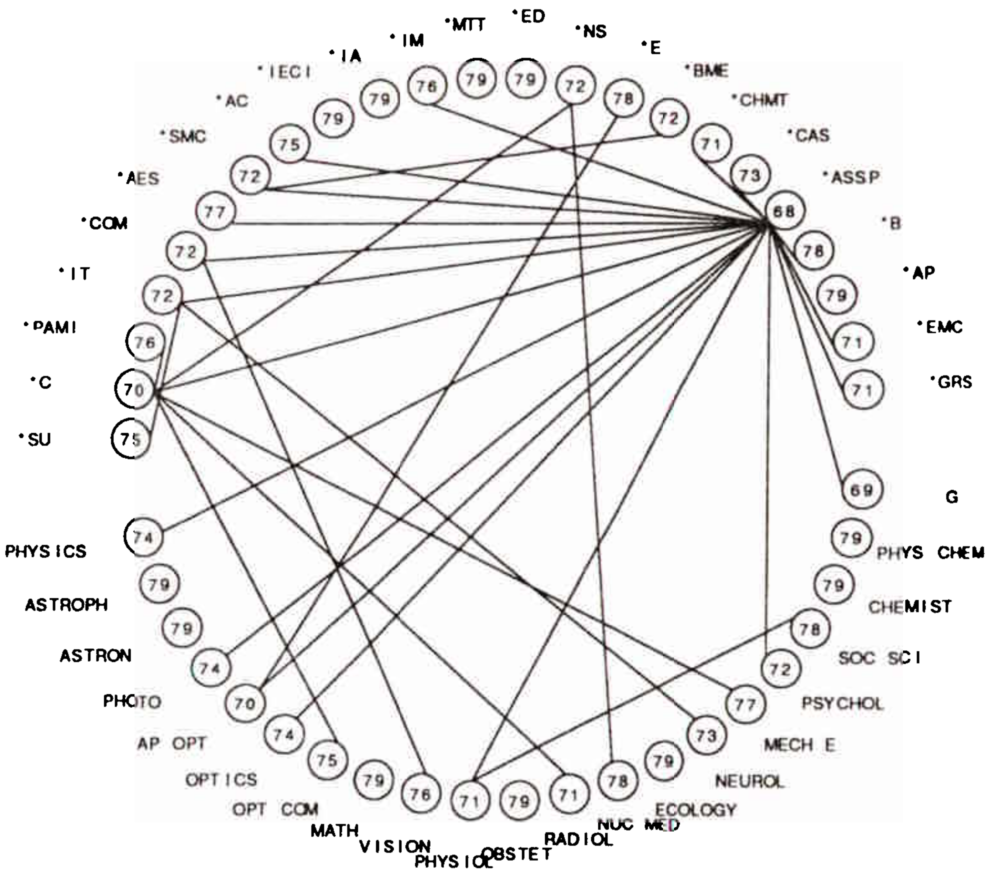


FIGURE 8. Observed initial diffusion path for Homomorphic Signal Analysis—HSA1. The number in the circle indicates the year in which that field first accepted the method of Homomorphic Signal Analysis given that they received it from one of the fields in the formal organizational structure. Each line indicates the path of the initial citation for the new field. For example, the initial article appeared in an article associated with *ASSP—Acoustics, Speech, and Signal Processing* in 1968. In 1969 an article associated with *G—Geology* appeared which cited the original article. The line between the fields *G* and *ASSP* denotes this citation. The density of lines to the sub-discipline *ASSP* is largely due to citation of the original article.

5.2. Impact of Formal Super-Communication Structure

The formal super-communication structure (Figure 9) shows a much higher level of interconnectedness between the fields. This is due to the fact that the two new generalist groups, readers of the *Proceedings of the IEEE* and readers of the *IEEE Spectrum*, serve as central nodes with ties to all the sub-disciplines in Electrical Engineering. All members of the IEEE receive *IEEE Spectrum* and *Proceedings of the IEEE*. These journals, especially the *Proceedings of the IEEE* are critical information servers for the discipline of Electrical Engineering. It is often the case that major works and important results are published in the *Proceedings of the IEEE*; e.g., Oppenheim's initial article appeared in the *Proceedings of the IEEE*. There is also a tie between *Proceedings of the IEEE* and *PHYSICS*, which re-affirms the closeness of the two disciplines, i.e. *Electrical Engineering* and *PHYSICS*.

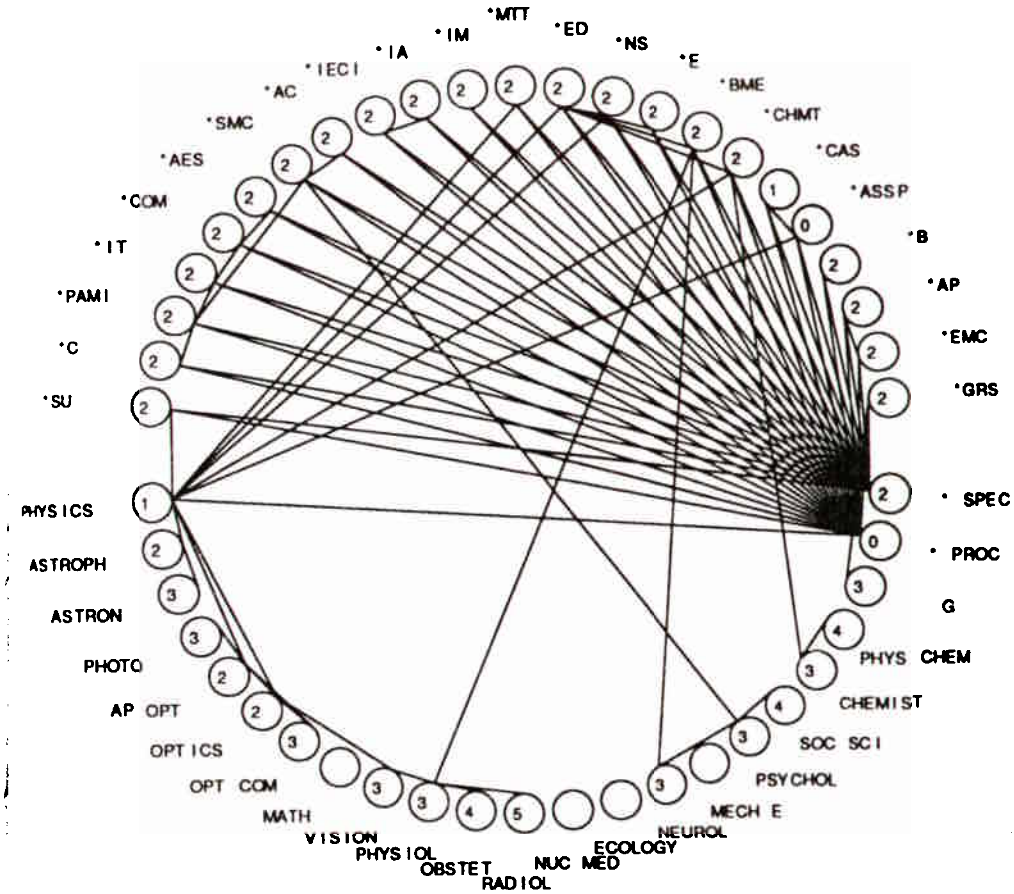


FIGURE 9. Formal super-communication structure. This figure shows the formal super-communication structure. Note: the fields include the 44 formal fields and the two generalist journal readerships. Each line indicates that the connected sub-disciplines have a cross citation rate of at least 5% and a total of more than 5 citations. Since all members of the IEEE regardless of discipline receive both the *Spectrum* and the *Proceedings* these two fields are connected to all of the sub-disciplines in IEEE. Note: only *PHYSICS* of the non IEEE fields is connected to the *Proceedings* and no non IEEE field is connected to *Spectrum*. Due to the influence of these generalist journals, no field in IEEE is more than 2 steps from the initiating field—*ASSP—Acoustics, Speech, and Signal Processing*. Since the originating article appeared in the *Proceedings* and is associated with the sub-discipline of *ASSP—Acoustics, Speech, and Signal Processing* both fields are marked as initiating fields.

Given this structure if model 2, method as map, is correct then the first fields that are expected to pick up the method are *CAS—Circuits and Systems*, and *PHYSICS*. Their tie to *Proceedings of the IEEE* serves to re-enforce their existent tie to the initial area of application *ASSP—Acoustics, Speech, and Signal Processing*. Since *Proceedings of the IEEE* and *IEEE Spectrum* serve as central dissemination nodes for the sub-disciplines of Electrical Engineering and since there is still little formal linkage to fields outside of Electrical Engineering then if model 2 is correct the sub-disciplines in Electrical Engineering should pick up the method before the other fields. Recall from Figure 7 that this is in fact the case. If model 1 is correct, and assuming uniform distribution of informal interaction ties, then the coupling of formal interaction and informal interaction ties should lead all sub-disciplines in Electrical Engineering and *Physics* to adopt the method at the same time.

Figure 10 portrays the observed initial diffusion path for Homomorphic Signal Analysis through the formal super-communication structure. The generalist journals play a central role in the diffusion process. The original article appeared in the *Proceedings of the IEEE* in 1968 and a year later Bergland published a related article in *IEEE Spectrum*. These two articles account for the majority of the initial diffusion of Homomorphic Signal Analysis. Although these two journals do not have formal ties to disciplines outside of IEEE, other than to *PHYSICS*, they do serve as major information servers to other fields. All but 6 of the fields outside of IEEE had an initial citation to either *Proceedings of the IEEE* or *IEEE Spectrum*. Other than these two journals the field of *C—Computer* serves as a major point for method diffusion.

The data in Table 2 suggests that given the formal super-communication structure model 2, method as map, is a better predictor of the observed diffusion path, especially within Electrical Engineering, than is model 1, method as grammatical production. Now, 382 of the 632 total citations (60.4%), 63 of the 145 unique (43.4%), and 29 of the 62 initial citations (46.8%) are correctly predicted by the structure. The distance metric provides further indication that model 2 is a better predictor. Now, 629 (99.5%) total citations, 142 (97.9%) unique, and 59 (95.2%) initial citations are correctly predicted by the formal super-communication structure. Looking at the time dependent data, however, model 1 appears to do slightly better. With a lag of one year 9 of the fields initially accepted the method at the appropriate time and 4 fields had early acceptance. With a laag of two years 10 of the fields initially accepted the method at the appropriate time and 22 fields had early acceptance.

Contrasting Table 2 with Table 1 shows that the generalist journals play an important role in method diffusion. The generalist journals are not needed for method diffusion; i.e. in both tables the distance metric shows that in most cases the method can be communicated via just the formal connections between the fields. When these journals are included, however, the structure does conform more closely to the citation pattern, especially within Electrical Engineering. And there is an increase in the number of total citation matches from 22.8% to 60.4%, and in the initial diffusion matches from 15.8% to 46.8%. Within Electrical Engineering there is an increase in the percentage of correctly predicted total cites from 12.0% to 85.3% and in the percentage of correctly predicted initial cites from 11.1% to 90.3%. Excluding citations to the generalist journals makes it appear that in 10 years only 33

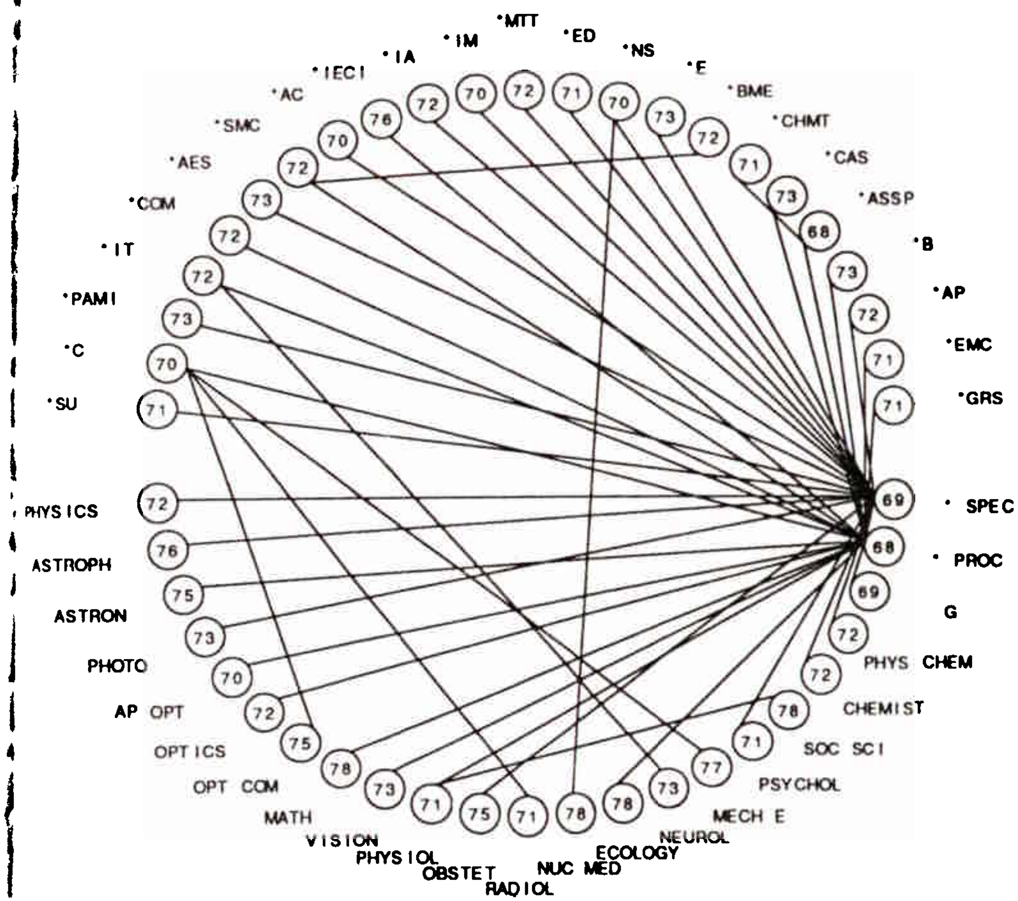


FIGURE 10. Observed initial diffusion path for homomorphic signal analysis—HSA2. The number in the circle indicates the year in which that field first accepted the method of Homomorphic Signal Analysis from a field in the formal super-communication structure. A line represents the initial diffusion path. For example, the initial article appeared in an article in the *Proceedings of the IEEE* in 1968. In 1969 an article associated with *G—Geology* appeared which cited the original article. The line between the field *G* and the *PROC* denotes this citation. The density of lines to *PROC* are largely due to citation of the original article.

fields have adopted the method; whereas, when including these citations 44 fields have adopted the method in 10 years.

Including the generalist groups increases the support for model 2, method as map, and decreases the support for model 1, method as grammatical production. Contrasting Table 1 and Table 2 we see that with either a lag of 1 or 2 the number of early cites tend to decrease and the number of on time cites tend to increase. The systematicity of these changes suggest that model 2 is the better predictor.

TABLE 2
Diffusion via the Formal Super-communication Structure—HSA2

	All Fields				Only IEEE			
	Total	Unique	Initial	Field	Total	Unique	Initial	Field
Totals	632	145	62	46	401	74	31	23
Ascribed Diffusion								
Matches	382(60.4)	63(43.4)	29(46.8)	NA	342(85.3)	54(73.0)	28(90.3)	NA
Misses	250(39.6)	82(56.6)	33(53.2)	NA	59(14.7)	20(27.0)	3(9.7)	NA
Lag 1								
Early	13(2.1)	13(9.0)	9(14.5)	4(8.7)	4(1.0)	4(5.4)	2(6.5)	0(0.0)
On Time	20(3.2)	17(11.7)	9(14.5)	11(23.9)	11(2.7)	9(12.2)	5(16.1)	5(21.7)
Late	599(94.8)	114(78.6)	44(71.0)	31(67.4)	386(96.3)	60(81.1)	24(77.4)	18(78.3)
Lag 2								
Early	67(10.6)	49(33.8)	27(43.5)	23(50.0)	21(5.2)	18(24.3)	8(25.8)	9(39.1)
On Time	48(7.6)	21(14.5)	8(12.9)	11(23.9)	29(7.2)	9(12.2)	5(16.1)	8(34.8)
Late	517(81.8)	74(51.0)	27(43.5)	12(26.1)	351(87.5)	46(62.2)	18(58.1)	6(26.1)
Distance Metric								
Matches	629(99.5)	142(97.9)	59(95.2)	NA	401(100.)	74(100.)	31(100.)	NA
Misses	3(0.5)	3(2.1)	3(4.8)	NA	0(0.0)	0(0.0)	0(0.0)	NA

Moreover, a close inspection of Figures 7 and 10 reveal that while the structure does not predict the timing of diffusion on a year to year basis, it does predict the general timing. In general the method of Homomorphic Signal Analysis diffuses to the IEEE sub-disciplines prior to the fields outside of the IEEE. Within Electrical Engineering 6 of the 8 sub-disciplines in the IEEE that have a distance of at most 3 units away from the originating field have started using the method of Homomorphic Signal Analysis by 1972. Only *E—Education* and *CAS—Circuits and Systems* delay usage to 1973. Of the 14 IEEE sub-disciplines that are 6 or more units away from the originating field 9 start using the method in 1972 or after. Of the 4 non-IEEE fields that are within 2 units of the originating field 3 had referred to the method by 1972. Whereas, of the remaining 17 non-IEEE fields 11 only began using the method after 1972. Moreover, 3 of the 4 fields that are not connected to the originating field did not receive the method until 1977 or 1978. The 4th such field, *G—Geology*, once the generalist journals are included, is the only one of the 4 that ends up being connected to the originating field.

Further, some of the sub-disciplines in IEEE that were early receivers that are not connected to the originating field received the method from a field to which they are closely connected. For example, *GRS—Geoscience and Remote Sensing* is one of the first IEEE sub-disciplines to adopt Homomorphic Signal Analysis and yet, according to the formal network, they should be one of the last. The method diffused to *GRS* early, however, not through IEEE channels, but from *G—Geology* from which it is only a unit away.

5.3. Impact of Functional Organizational Structure

The functional organizational structure (Figure 11) is the day-to-day working connections between the sub-disciplines in Electrical Engineering as exhibited by opinion leaders. Figure 11 shows that the discipline is tightly interconnected due to the scientists' chosen research areas. Many disciplines are only two steps apart. Since formal boundaries are irrelevant to model 1, method as grammatical production, the three structures should have similar predictive power. Whereas, if model 2, method as map, is correct the functional organizational structure should have less predictive power than the formal structures, as the level of shared knowledge between groups is less than in the formal organizational structures.

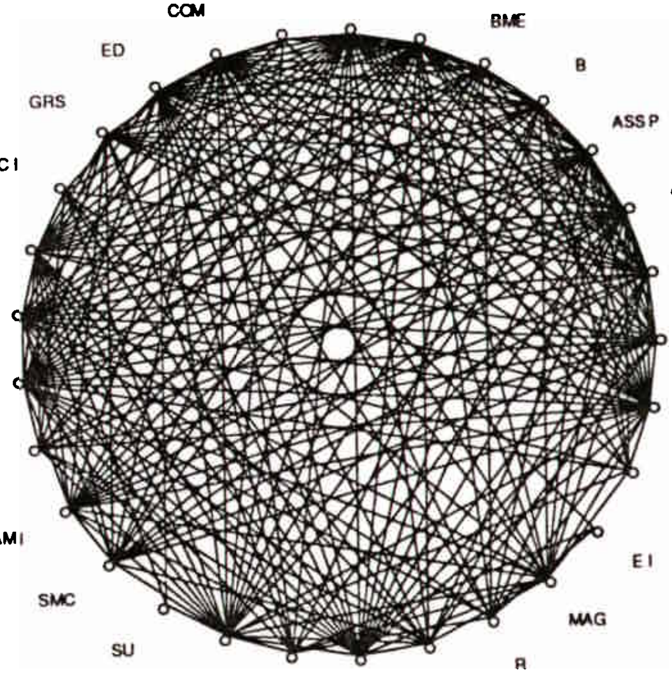


FIGURE 11. Functional organizational structure. This figure shows the pattern of ties resulting from the research interests of Electrical Engineers at Berkeley, CMU, Stanford, and MIT. These researchers identified 29 IEEE sub-discipline, those shown, as the fields in which they work. A line indicates that at least one researcher in one of these top schools in Electrical Engineering does research in both of the connected sub-disciplines. This figure is thought of as the working or informal topology in the discipline of Electrical Engineering.

Scientists do transfer formal knowledge between sub-disciplines. Thus the lack of segmentation in the scientist's research interests in Electrical Engineering should facilitate rapid communication even under model 2. Which is the case. Figure 6 showed that by 1973 22 of the 23 sub-disciplines in Electrical Engineering that were to use Homomorphic Signal Analysis in the first 10 years had already done so. The remaining area, *IECI—Industrial Electronics and Control Instrumentation*, did not

TABLE 3
Diffusion via the Functional Organizational Structure—HSA3

	Total	Only IEEE Unique	Initial	Field
Matches	88(88.0)	30(85.7)	15(83.3)	NA
Misses	12(12.0)	5(14.3)	3(16.7)	NA
Total	100	35	18	23
Lag 1				
Early	5(5.0)	5(14.3)	3(16.7)	7(30.4)
On Time	1(1.0)	0(0.0)	0(0.0)	1(4.3)
Late	94(94.0)	28(80.0)	15(83.3)	15(65.2)
Lag 2				
Early	9(9.0)	7(20.0)	5(27.8)	8(34.8)
On Time	6(6.0)	4(11.4)	2(11.1)	2(8.7)
Late	85(85.0)	22(62.9)	11(61.1)	13(56.5)
Distance Metric				
Matches	99(99.0)	34(97.1)	17(94.4)	NA
Misses	1(1.0)	1(2.9)	1(5.6)	NA

receive the method until 1976 and is one of the most industrial oriented fields to which the method dispersed.

Table 3 contains data on the impact of the functional organizational structure. Within Electrical Engineering this structure predicts 88 (88.0%) of the total citations and 15 (83.3%) of the initial citations. Using the distance metric, the degree of prediction is even higher—99 (99.0%) of the total citations and 17 (94.4%) of the initial citations. Both the ascribed diffusion and the distance metric supports model 2. The lag data, however, slightly supports model 1.

Table 4 shows the relative impact of the three structures for fields in Electrical Engineering. When the citations that occur in the generalist journals are excluded, the formal organizational structure accounts for 13 (13.0%) of the total citations and 3 (16.7%) of the initial citations. Whereas, the functional organizational structure accounts for 88 (88.0%) of the total citations and 15 (83.3%) of the initial citations. This suggests that although shared formal knowledge is necessary for adoption, the most likely interaction ties to effect diffusion are those formed through cross field research. When the articles in the generalist journals are taken into account a different picture forms. The formal super-communication structure matches the observed diffusion path the best when the exclusive impact of the three structures is shown. This suggests that model 2 is the better predictor.

5.4. Impact of Personal Contact

When the formal super-communication structure and the functional organizational structure are combined the predictive power directly increases only for the initial citations. This suggests that, although most diffusion follows the formal structure, the few times that it does not are due to personal contact. Note: in Table 2, 5 fields are listed as receiving the method early. These fields and the year in which they started using Homomorphic Signal Analysis are: *Ecology* 1978, *Math* 1978, *Mech E—Mechanical Engineering* 1977, *Radiology* 1971, and *G—Geology* 1969. The first three of these fields are receiving the method early, by definition, because in the formal topology they are more than 10 units away from the originating field. Both *Radiology* and *Geology* can be reached from the originating field. Of these two fields *Geology* is the further from the originating field and yet, it is the very first field to pick up the method.

TABLE 4
Relative Impact of Structures

	Total	Only IEEE Unique	Initial
Ascribed Diffusion—Matches			
Formal Organizational	13(13.0)	7(20.0)	3(16.7)
Functional Organizational	88(88.0)	30(85.7)	15(83.3)
Collectively	88(88.0)	30(85.7)	15(83.3)
Total	100	35	18
Ascribed Diffusion—Matches			
Formal Organizational	13(3.2)	7(9.5)	3(9.7)
Formal Super-communication	342(85.3)	54(73.0)	28(90.3)
Functional Organizational	88(21.9)	30(40.5)	15(48.4)
Collectively	392(97.8)	71(95.9)	30(96.8)
Total	401	74	31
Ascribed Diffusion—Matches—Exclusive			
Formal Organizational	9(2.3)	4(5.4)	0(0.0)
Formal Super-communication	333(83.0)	50(67.6)	28(90.3)
Functional Organizational	59(14.8)	21(28.3)	2(6.5)
Collectively	392(97.8)	71(95.9)	30(96.8)
Total	401	74	31

The method of Homomorphic Signal Analysis diffused to *G—Geology* through personal communication. For a long time, T. J. Ulrych[36] had been interested in communications related ideas and how they might relate to geophysics. As he did not always keep up with the Electrical Engineering literature it might have been several years before he heard of Homomorphic Signal Analysis if it were not for fate. Fate took the form of a man, Sphen Treital. At the time, Treital was in industry: he was employed at AMOCO. Treital just happened to keep up with the Electrical Engineering literature, and so he read the original 1968 article in the Proceedings of the IEEE. Knowing of Ulrych's interest, he related the information to his friend. Knowledge of both Electrical Engineering and *Geology*, as well as informal interaction were necessary for this communication to take place.

[36] Although Ulrych was not the first to use Homomorphic Signal Analysis in Geology the papers he wrote were some of the most influential in bringing themethod to this field. The earlier work on Cepstral analysis by Bogert, Healy, and Tukey had excited the interest of some of these geophysicists. They were, to some extent, keeping up with trends in Electrical Engineering. But, it was not until Oppenheim generalized the method that it became really useful to them.

TABLE 5
Inter-field Diffusion Data—HSA4

	All Citations				Citations not to Original			
	All Fields		Only IEEE		All Fields		Only IEEE	
	Total	Initial	Total	Initial	Total	Initial	Total	Initial
Totals	116	28	80	17	75	18	52	9
Ascribed Diffusion								
Matches	79(68.1)	19(67.9)	70(87.5)	14(82.4)	50(66.7)	11(61.1)	42(80.8)	6(66.7)
Misses	37(31.9)	9(32.1)	10(12.5)	3(17.6)	25(33.3)	7(38.9)	10(19.2)	3(33.3)
Lag 1								
Early	7(6.0)	3(10.7)	5(6.3)	1(5.9)	7(9.3)	3(16.7)	5(9.6)	1(11.1)
On Time	9(7.8)	4(14.3)	4(5.0)	1(5.9)	9(12.0)	4(22.2)	4(7.7)	1(11.1)
Late	100(86.2)	21(75.0)	71(88.8)	15(88.2)	59(78.7)	11(61.1)	43(82.7)	7(77.8)
Lag 2								
Early	21(18.1)	9(32.1)	10(12.5)	3(17.6)	21(28.0)	9(50.0)	10(19.2)	3(33.3)
On Time	9(7.8)	4(14.3)	8(10.0)	3(17.6)	6(8.0)	2(11.1)	6(11.5)	2(22.2)
Late	86(74.1)	15(53.6)	68(77.5)	11(64.7)	48(64.0)	7(38.9)	36(69.2)	4(44.4)
Distance Metric								
Matches	116(100.)	28(100.)	80(100.)	17(100.)	75(100.)	18(100.)	52(100.)	9(100.)
Misses	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	0(0.0)

5.5. Impact of Citation Norms

Regardless of the structure used the timing of the diffusion is not accurately predicted. There are a variety of possible reasons. It could be that the appropriate model is model 1, method as a grammatical production, however, if this were the case there should not have been the systematic improvement in the predictive power of the formal structure as the generalist groups were added. Alternatively, factors such as research agendas and publication delays may affect the actual timing of the ascribed diffusion. Citation norms might also affect the ascribed diffusion. For example, a plausible norm would be *always cite the initial article*. Given this norm one might erroneously conclude that diffusion occurred from the field of the original article to the field of the citing article, even though diffusion actually occurred through a field of the original article to the field of the citing article, even though diffusion actually occurred through a different route. An original citation norm would make the ascribed diffusion appear to be better predicted by model 1, method as grammatical production, than model 2, method as map.

Among the citations in HSA2 are a set of 50 articles that cite both the original article and at least one other article that cited the original article. This provides a total of 155 cites, 116 of which are inter-field cites. This data is referred to as HSA4. Table 5 provides the diffusion data for these inter-field cites, and for those cites in HSA4 that are not to the original article.

The impact of an original citation norm can be seen by contrasting the left and right hand side of Table 5. Whether or not citations to the original article are included, the formal super-communication structure predicts most of the citations. When the original citation norm is taken into account, the timing of the diffusion

follows, somewhat more closely, the formal connections between the fields. Since the original article appeared in a generalist journal, *Proceedings of the IEEE*, most references to this article appear to be late as this journal is central to the network, especially, within Electrical Engineering. In this case, the original citation norm makes it appear that the method is diffusing as though model 1, method as grammatical production, is correct; whereas, when this norm is accounted for the method diffuses as predicted by model 2, method as map.

6. DISCUSSION AND SUGGESTIONS FOR FUTURE RESEARCH

The results presented depend on the way in which the diffusion path and the structures are measured. Thus, future research should address the following concerns. Citation paths may serve as proxies for actual diffusion paths; consequently, one might consider using another method for locating the actual diffusion path. Articles can be mapped onto fields in a variety of ways other than by journal identification. Alternate classification schemes such as ones based on the author's current official position or field of research need to be considered. Various algorithms for deciding on a method's diffusion into a field need to be compared. And finally, alternate field classification schemes and the robustness of structural ties should be considered.

Heterophilous communication leads to message distortion (Barnlund and Harland, 1963). Generalist journals serve as central dissemination nodes and increase the homophilly of the group thus they should decrease message distortion and admit more rapid diffusion of innovative methods. This was found to be the case although the effect is primarily within the discipline. Further, for Homomorphic Signal Analysis the generalist journals accounted for most of the diffusion. This made it appear that diffusion was not affected by the formal sub-discipline boundaries. It is possible that such journals actually increase the differences between disciplines by more clearly demarcating the social boundaries. Thus one expects that methods published in a sub-discipline specific journal will diffuse more quickly to external disciplines and less quickly to sub-disciplines within the originating discipline. Whereas, if the method is published in a generalist journal then it should diffuse more quickly to the associated sub-disciplines and less quickly to external disciplines. This is a question for future research.

Rapoport (1953, p. 15) suggested that there might be a tradeoff between the speed and efficiency of information transmission. In the case of Homomorphic Signal Analysis, at the structural level, this does not appear to be case. Within Electrical Engineering generalist journals, serve as a central market admitting both rapid and efficient diffusion. Such journals may even facilitate rapid and efficient diffusion to fields outside of Electrical Engineering by providing a focal point for those outside of the discipline. This suggests there is not, *a-priori*, a simple tradeoff between speed and accuracy.

As scientists, we want to assign validity only to those methods that are context free; i.e. we want to believe that the method we are using is independent of the specific data being analyzed, that it can be used on other data sets, and that it can be used across disciplines. Consequently, we would like methods to have the cognitive properties of grammatical productions. As researchers, we are aware of the fundamental fact that the type of data to be analyzed and the type of question posed limits the choice of method. Consequently, we expect methods to have the cognitive properties of maps. In the scientific community, the scientific model of analysis and the pragmatic research tradition are superimposed. This creates a paradoxical environment *vis-a-vis* the use and communication of methods. Promotion of the scientific mode of analysis and the pragmatic research tradition generally require and are nurtured by fundamentally different behaviors on the part of the individual scientists. This leads to norms in citation behavior that obscure the actual diffusion path. Scientists may be using citations to argue the validity of the method by suggesting its cross-field applicability rather than utilizing citations to indicate the historical development of their work. This study suggests that citation norms obscure but do not affect the diffusion path. Citation norms other than the one looked at should be explored.

This study suggests that generalist journals can serve to maintain and nurture both traditions. Such journals redefine validity at the discipline level; i.e. publication in and reference to work in such a journal has validity across the associated sub-disciplines. In Electrical Engineering the generalist journals maintain and nurture the objectivistic tradition by providing intra-discipline validity thus making methods appear to have the cognitive properties of grammatical productions. These journals also maintain and nurture the pragmatic research tradition by increasing the number of knowledge and interaction ties within the discipline; thus decreasing the distance between sub-disciplines and facilitating the diffusion of methods as maps.

From an organizational standpoint, diffusion is predictable. The pattern of diffusion is as prescribed by the formal super-communication structure but not the exact timing of the diffusion. Once citation norms are accounted for, the formal super-communication structure more accurately predicts the timing of the diffusion. Further, the more comprehensive the structure used the better the diffusion prediction. From a cognitive standpoint, this research suggests a possible cognitive foundation for method diffusion—methods as maps which are tightly coupled to the area of application and are communicated on the basis of the level of shared knowledge and interaction. Consequently, both knowledge and interaction ties are necessary for method diffusion. From a scientific communication point of view, generalist journals which are central nodes for a discipline serve an important function in intra- and inter-discipline communication. From the individual scientist's point of view publication in such journals leads not only to wide readership but rapid diffusion of the ideas. When such journals publish innovative methods they encourage innovation and the adoption of new methods. The second major structural factor in the rapid diffusion of innovative methods is that opinion leaders tend to work in a cross-sub-disciplinary fashion. The importance of such co-membership in sub-disciplines is that it allows the transfer of sufficient knowledge that innovative methods can be rapidly assimilated.

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APPENDIX 1

AC	Automatic Control Systems
AES	Aerospace and Electronic Systems
AP	Antennas and Propagation
APOPP	Applied Optics
ASSP	Acoustics, Speech, and Signal Processing
B	Broadcast, Cable and Consumer Electronics
BME	Engineering in Medicine and Biology
C	Computer
CAS	Circuits and Systems
CATV	Cable Television
CE	Consumer Electronics
CHMT	Components, Hybrids, and Manufacturing Technology
COM	Communications
E	Education
EC	Electromagnetic Compatibility
ED	Electron Devices
EE	Electrical Engineering
EI	Electrical Insulation
EMR	Engineering Management
G	Geology
GRS	Geoscience and Remote Sensing
IA	Industry Applications
IECI	Industrial Electronics and Control Instrumentation
IM	Instrumentation and Measurement
IT	Information Theory
JOE	Oceanic Engineering
JQE	Quantum Electronics and Applications
MAG	Magnetics
MTT	Microwave Theory and Techniques
NS	Nuclear and Plasma Sciences
PAMI	Pattern Analysis and Machine Intelligence
PAS	Power Engineering
PROC	Proceedings of the IEEE
R	Reliability
SE	Software Engineering
SMC	Systems, Man and Cybernetics
SPEC	IEEE Spectrum
SSC	Solid State Circuits

SU Sonics and Ultrasonics
VT Vehicular Technology

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ANALYZING CONTINUOUS STATE SPACE FAILURE TIME PROCESSES: TWO FURTHER RESULTS*

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In a recent paper, Petersen (1988) considered a continuous state space failure time process. The central result provided in that paper was that the destination-specific rate of transition of the process can be specified in two steps. First, one specifies the overall rate at which a change occurs. Then, one specifies the probability density function of the destination state, given that a transition occurred. This two-step property was used in deriving the likelihood of the data and was exploited for purposes of estimation. The overall rate of transition can be estimated from the data on durations between changes in the dependent variable. The density for the new value of the dependent variable, given a change, can be estimated from the data on the values of the dependent variable after the change.

This paper extends these results in two ways. First, it is shown that one can derive the likelihood of the process directly from the destination-specific rate of transition, without going through its decomposition into the overall rate times the density of the destination state, given a transition. Once the likelihood is derived, estimation is comparatively straightforward. Second, it is shown how one can derive, at each point in time, a more standard regression function for the continuous dependent variable, where its value is expressed in terms of its conditional mean plus an error term.

KEY WORDS: continuous state space failure time processes, parametric hazard rate models, maximum likelihood estimation, socioeconomic status histories.

1. INTRODUCTION

In a recent paper, Petersen (1988) considered a continuous state space failure time process. The dependent variable is continuous. Over time it evolves as follows. For finite periods of time—that is, from one calendar date to another—it stays constant at a given value. At a later date, which is a random variable, the dependent variable jumps to a new value, and this jump can be of any size and in any direction. The process evolves in this manner from the calendar date when one change occurs to a

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