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THE POSSIBILITY OF A MATHEMATICAL SOCIOLOGY OF SCIENTIFIC COMMUNICATION

LOET LEYDESDORFF

SUMMARY. The focus on discourse and communication in the recent sociology of scientific knowledge offers new perspectives for an integration of qualitative and quantitative approaches in science studies. The common point of interest is the question of how reflexive communication systems communicate. The elaboration of the mathematical theory of communication into a theory of potentially self-organizing entropical systems enables us to distinguish the various layers of communication, and to specify the dynamic changes in these configurations over time. For example, a paradigmatic discourse can be considered as a virtual communication system at the supra-individual level. Communication systems, however, cannot be directly observed. One observes only their instantaneous operations. The reflexive analyst is able to attribute the observed uncertainty to hypothesized systems that interact in the events. The implications of this perspective for various programmes in the sociology of scientific knowledge are discussed.

Key words: Scientometrics, communication, sociology of knowledge, self-organization.

INTRODUCTION

One of the major objections against scientometrics from the qualitative side of science studies has been that reality is too complex to fit nicely into the idealized models which scientometricians have proposed (see, e.g., Edge, 1979; Chubin and Restivo, 1983). As long as we do not understand how the sciences are contingently constructed, it is not informative to tell a "great story" in structural terms. The scientometrics enterprise, however, indicates that there is also a sense in which the sciences are amenable to measurement even if, for the time being, one is not able to understand what scientometric indicators mean in other than pragmatic terms. Hitherto, scientometrics as a methodology has remained in need of "a theory of citation", or, more generally, a theory of scientific communication (e.g., Cronin, 1981; MacRoberts and MacRoberts, 1987).

In the last decade, the sociology of scientific knowledge has increasingly focused on discourse (e.g., Mulkay *et al.*, 1983) and communication systems or "actor networks" (Callon *et al.*, 1986). These theories inform us about the specificities of scientific communication systems. For example, if scientific "groups" are considered as local networks that link into scientific "fields" as more global network (Pinch 1985; Callon *et al.*, 1986), such a formulation signals the crucial mechanism of communication. However, the theoretical analysis does not yet provide us with clarity about how to relate the complexity, the reflexivity, and the fluidity of this operation.

Communication is a complex process that cannot be taken unproblematically as a basis for understanding. Scientometric operationalization has focused on the communication of information, while concepts like "networks", "structure", etc., are used in postmodernist sociologies and semiotics mainly for studying the generation, communication, and decoding of meaning (e.g., Eco, 1976; Courtial, 1989). In the mathematical theory of communication (Shannon, 1948), information has been defined as content-free, i.e., as whatever communication systems communicate. Shannon, however, described communication in a fixed channel, while social communications are part of communication systems that may change structurally by operating. For such systems each communication may make a difference in the time dimension. This reflexive information has also been identified with "meaning" or "meaningful information" (e.g., MacKay, 1969; Bailey, 1990).

Self-organizing systems (e.g., Prigogine and Stengers, 1979; Maturana and Varela, 1980) are additionally able to select among reflexive meanings. Thus, self-organizing systems are communicative in relations (first dimension), able to position the information (because of differentiation in a second dimension), able to reflect on the information (using time as a third dimension), and additionally able to reflect on the arrangement in these three dimensions in a fourth dimension. Models for parallel and distributed processing enable us to study such systems (cf. Rumelhart *et al.*, 1986; Langton *et al.*, 1989 and 1992). Luhmann (1984) proposed the study of social systems from this perspective, and more recently Luhmann (1990) has elaborated the theory of self-organization for the sciences as complex and developing communication networks. I shall argue that the possibility of combining sociological theorizing with mathematization about communication systems enables us to reformulate the tension between qualitative theorizing in the philosophy, sociology and history of science and the quantitative perspectives provided by scientometrics, yet without directly necessitating quantitative measurement or numerical computation (Krippendorff, 1986).

THE CONCEPT OF PROBABILISTIC ENTROPY

Hayles (1990) has noted that Shannon's (1948) decision to equate expected information with *uncertainty*, and to choose a mathematical identity in the formulas for information and entropy, has been extremely parsimonious.¹ The resulting concept of communication is highly abstract: it specifies communication as an operation that generates probabilistic entropy or, in other words, communicates information. Since communication, probabilistic entropy and information are here defined as content-free, these concepts precede their operationalization. Probabilistic entropy can be considered as a dynamic equivalent of concepts like "degree of freedom" or "dimension" in the static analysis.

A concept is by definition cognitive and reconstructive. "Probabilistic entropy", however, captures an operation. Since the measurement itself is an operation, this concept is additionally recursive – i.e., it can be applied to the results of its own measurement. Consequentially, the mathematical theory of communication enables us to study both communication systems and the communications among them, i.e., to systematically distinguish among different levels of communication and to relate the results of these observations reflexively (cf. Leydesdorff, 1992a).

The advantages for the further development of the sociology of scientific knowledge are manifold. First, since probabilistic entropy can be considered as a measure of complexity (Theil, 1972), the mathematical theory of communication enables the analyst to relate the uncertainty in the content of scientific knowledge systematically with variation in its social and cultural production systems (cf. Whitley, 1984). Each variance contains an *uncertainty* which can also be expressed in terms of the expected information content of a message.² Since information and its communication are defined mathematically, and are therefore content-free, the analyst gains access to the study of interactions and relations which hitherto remained the domains of separate fields of study. All observations can be reconstructed and evaluated in terms of their expected information value (cf. Theil, 1972; Krippendorff, 1986). For example, by using information calculus one is able to relate the variance in sociological data with probability distributions for scientific hypotheses (e.g., Hesse, 1974; Howson and Urbach, 1989) or co-occurrences of words in scientific texts (cf. Hesse, 1980; Callon *et al.*, 1983). All these uncertainties can be considered as dimensions of the probabilistic entropy of the system(s) under study.

Secondly, in addition to the analysis of relations, all formulas can be developed into dynamic equivalents so that the time dimension can be addressed systematically (cf. Theil, 1972; Leydesdorff, 1991). For example, the scientific journal system by operating produces a yearly distribution of publications (citations, etc.) over nations. But what do these variations indicate? The observed distributions can be assessed with reference to different systems, e.g., the journal system, the division of scientific labour over nations, and/or the development of the international science system. With reference to which system(s) do the indicators exhibit change, and which systems were (sometimes implicitly) presumed to remain stable during the period under study? When is change to be considered as significant, structural and/or irreversible? Using information theory, the uncertainty which is observable at different moments in time can be understood as part of the probabilistic entropy of the system(s) which generate(s) this variation over time (cf. Leydesdorff, 1992b).

Thirdly, since entropy measures can be written as a summation (Σ), this methodology allows for the modelling of uniqueness: any development can be considered as a result of discrete events. Communication systems operate by communicating information with other communication systems in

contingent, i.e., historical relations. The observable data is then considered as information that is communicated among communication systems which themselves contain only expectations. The historical uniqueness of the events is a consequence of the contextual complexity (and not the other way round). However, if the historical development is *not* to be considered only in terms of what can be observed, one has to specify also the systems that communicate through this data.

THE HYPOTHESIS OF SELF-ORGANIZING SYSTEMS

How can one delineate the relevant communication systems in empirical research? A delineation at one moment in time would not serve, since communication systems change over time. As noted, the observed data indicate interaction among the systems, and, therefore, one may expect these systems to have changed after interaction. How can they maintain structure over time despite changes and variation in the observable phenomena?

A communication system operates through the deconstruction of relations among its composing lower-level units, and their reconstruction into a new (i.e., updated) structure. By relating in the network, in terms of aggregations and disaggregations, and over time, the “actants” – i.e., whatever may be relating given the nature of the communication – develop a network with an architecture. When written as a matrix, this architecture can be analyzed in terms of its so-called eigen-structure; and when repeated over time, these structures may be expected to contain eigen-time, i.e., options for further developments which are more or less likely to occur.

In a matrix representation, the “actants” are conventionally shown as row vectors, and communications as column vectors. The observed communication of an uncertainty (e.g., the change of a cell-value) has an update value for all systems involved: it informs us not only about external references to the communications, but also about the behaviour of the communicating systems over time. Additionally, the option to vary among the delineations of multi-variate datasets and the lengths of time-series provides the analyst with yet another degree of freedom. The duality of the reconstruction in terms of eigen-structure *and* eigen-time allows him/her to distinguish datasets which increasingly behave as distributed identities, i.e., which tend to maintain their (complex) structure over time (cf. Dosi, 1982).

Structure, stability, and distributed identities or regimes, however, remain hypotheses, since they have to be inferred on the basis of a reconstruction. In other words: the analyst can reconstruct the state of the system in terms of its eigen-structure. This eigen-structure can be pronounced, and the specific pattern can also be maintained self-referentially. Time series of data can be assessed on whether a system can be expected to have developed an eigen-time (e.g., a life-cycle). In the degree of freedom between eigen-structure and eigen-time, one can finally hypothesize that the system has

options to organize itself increasingly in terms of its operation. The self-organizing system can be considered as the construction which is able to use this degree of freedom for maintaining the character of its communication over time, despite alternatives. The expectation values for the entropies on the basis of the *hypothesis* of self-organization ("autopoiesis") can be tested against the variance in the data which are to be observed: if a complex data structure operates as a system, it is expected to exhibit other (co-) variations than when its elements change independently; a self-organizing system is also expected to recover from temporary losses of structure.

For example, the clear factor structures which have so often been reported from studies of aggregated journal-journal citation data (e.g., Carpenter and Narin, 1972; Doreian and Farraro, 1985; Leydesdorff, 1986; Tijssen *et al.*, 1987) are not the incidental results of one clustering algorithm or another on this "data" as given in a natural history: they are rather the results of operations (i.e., "facta") among the various specialty structures involved. There is nothing in these journals which make them cluster, except that they refer to specialties and disciplines as higher-order communication systems (cf. Leydesdorff and Cozzens, 1993). These cycles of communication are not observable in terms of communicating agents (i.e., the citing texts in the journals), but they can be analytically distinguished as virtual hypercycles of communication for explaining the observed structure and continuity in this data. When these higher-order systems of communication are hypothesized, they can sometimes be made visible by appropriate aggregation of the lower-level data.

Although the journals may vary, the clusters can exhibit a tendency to remain stable in the time dimension. By interpreting lower-level communications with reference to the higher-order system, hypotheses with respect to this latter system can be updated in terms of the composing units. The self-organizing systems and subsystems remain analytical possibilities which are contained in the empirical distributions. They should not be reified at the meta-level in terms of the gods and demigods who supposedly govern history. However, the eigen-vectors of eigen-structure and the eigen-frequencies of eigen-time cannot be attributed to any of the constitutive elements; they are latent properties of the matrix which represents the network, and of its development over time.

The situation is strictly analogous with nominal (e.g., historical) data, although the measurement scale is more relaxed: the analyst can only tell a story ("a reconstruction") on the basis of the (sometimes implicit) assumption that, for example, it was the science under study which, in order to develop, had to reorganize whatever relevantly happened in terms of what it meant for its structure, its historical development, and its identity. On the one hand, the analyst has to tell the story by using a *metaphor* that has to refer to a system in its environment. On the other hand, the system under study remains a construct, and reflexively the analyst should never reify its reconstruction. Alternative hypotheses can be tested by

comparing the observed variances with the expected ones during the operation of the hypothesized systems.

COMMUNICATION SYSTEMS

This definition of communication systems as probabilistic constructs highlights why it is not enough to study only the observable "interactions", for example, between social and cognitive developments (e.g., in terms of "socio-cognitive" actions).³ The observable interactions exhibit the mutual information or the co-variance among the hypothesized systems during the event of the operation. Additionally, the remaining variances in participating systems have to be specified. The sum of the co-variance and the remaining variance (i.e., the total variance) contains the information about the state of a given system, and is thus relevant for the expectation of the system's further development. Consequently, the observable interactions inform us only partially about the systems under study.

Not all communication systems can retain the probabilistic entropy, and only specific ones can use their history for their own further development. Luhmann (1984) postulated that social systems are communication systems that (among other things) reflexively process their history. Since the operation of a social network is different from that of individual actors, concepts like information, meaning and reflexivity have to be substantiated differently with reference to this system.

Historians and sociologists sometimes find it difficult to generate a semantics for communications that can have meaning for systems other than actors. However, one has to reverse the causality in the reasoning: communications can have meaning for actors, since actors are self-referential systems that can retain and internally process the information. In addition to the actors, the network can be considered as a relevant context for the interaction: what is action with reference to an actor, is communication with reference to a social network. These operations are orthogonal like the rows (which represent the actors) and the columns (which represent the communications) in a matrix representation. The co-variation between rows and columns can be given meaning with reference to both dimensions of the matrix. Over time, the interaction is generated both by the self-referential loop of the network, and by the self-referential loops of each of the actors involved. The systems inform one another mutually through the windows of these interactions.

Thus, the thesis is not that the network behaves like another actor, but that the dynamics of the two systems, including the question of how meaning is generated, can be analyzed within a single theoretical framework. These systems constitute relevant environments for one another; to the extent that they co-vary in the events, they inform one another about their behaviour. It depends on the substance of the system whether, and if so how, they are able to inform themselves about their relation with this

environment, i.e., whether and how they can use the information that they observe through the window of interaction for the further development of their expected information content (cf. Leydesdorff, 1992a).

Without the specification of the network as a system of reference, the analyst is at risk of attributing meaning to the wrong system, and consequently of category mistakes. For example, if a scientist communicates, this communication has more meanings than the (intentional) meaning which it has for the sender, and the various meanings which the message may be given at each receiving end of the communication. Additionally, the message takes place in the network of communication. This situational meaning can be processed reflexively ("translated") within this communication system *if* the network has previously gained a specific identity (e.g., a specialty structure).⁴

However, if the sociologist (or the historian) studies exclusively the scientists and their observable actions, both at the sending and at the receiving end of the communication, the additional meaning with reference to the network can no longer be specified. If subsequently one becomes aware of an additional (sociological) meaning that has to be attributed to the situation – i.e., not to any of the actors involved, but to their communication – this analyst would have no other frame of reference for the specification of this meaning than her own reflexive identity (cf. Woolgar, 1988). But what one has failed to distinguish empirically in the world, i.e., the network as a communication system, cannot fully be compensated for by resources which are internal to the analyst.

For example, in Pickering's (1992) collection of discussion papers in the sociology of scientific knowledge, subjective reflexivity prevails to such an extent that these scholars no longer need empirical data for the update of their expectations; they need this data at most to illustrate their programmatic claims about how the sciences should or should not be analyzed. Luhmann (1990) – and to a lesser extent, Collins and Yearley (1992) – have already formulated this critique of the recent sociology of scientific knowledge. However, these authors ultimately failed to elaborate an alternative in terms of empirical hypotheses which analytically relate the meta-theoretical reconstructions to the theoretical constructs under study in terms of expected and observable variances.

Luhmann (1984) identified the social system with communications among people, but did not formulate this sociology in relation to the mathematical theory of communication. Had he done so, he would have noted that communication is content free: all systems which process information are communication systems. As communication systems they can be identified in terms of the (hypothesized) substance of the information which they process. On the one hand, Luhmann's equation of society with *the* communication system, in contrast to, for example, individual consciousness systems ("actors"), highlighted the qualitative difference between the substantive meanings of information in either system, i.e., the "Sinn" of the

communication with reference to individuals and with reference to the relevant networks (cf. Habermas and Luhmann, 1971). On the other hand, this distinction obscured the underlying general dynamics of biological, psychological, sociological, and other entropical systems. All systems which process information (e.g., neural networks) are communication systems among other communication systems which by communicating make and possibly process their own history. However, *what* is communicated is specific to each system; systems should be delineated in terms of the substance of their transmission.

Communication systems can be coupled in *structural*, *operational* or *loose* interactions; correspondingly, they can communicate over time (i) with themselves, (ii) internally (e.g., among subsystems), and (iii) in relation to otherwise uncoupled systems (e.g., in organizations). Structurally coupled systems are caught in intersecting self-referential loops: they have to mutually communicate the information in their co-variation, and by doing so they are updated self-referentially. For example, social systems cannot operate unless actors operate. (In other words: the links in the network cannot exist without the nodes; the column vectors of a matrix are expected to co-vary with the row vectors). Structural coupling leads to the "mutual shaping" of systems by one another. But the meaning of the communication for either system is asymmetrical, since the percentage of co-variance in a given interface is assessed with reference to different total variances.⁵

Subsystems are coupled operationally, i.e., they do not have to update in reaction to one another after each iteration. Subsystems can be pressured by the system to operate if they fulfill specific functions. In the case of differentiation the content of communication is additionally specific at the level of each subsystem. Interaction can be considered as operational coupling through a medium of communication to which both (sub)-systems are structurally coupled. The medium can then be considered as the substance of a supersystem that can be empirically studied if it is properly specified (i.e., as a hypothesis). Note that operational coupling involves two communications: one between the sending and the transmitting system and one between the transmitting and the receiving system. Consequently, interaction between human beings using the social system is in principle non-linear.

In loosely coupled systems, membership is the independent variable, and the specificity of the communication is dependent upon this organizational boundary. If specific patterns of communication can be maintained among initially loosely coupled systems, a three-dimensional system is formed that can sometimes be stabilized (depending on whether its substance stores traces, i.e., contains a passive memory function). The self-organizing system contains a fourth degree of freedom, which enables it to select operationally among its stabilized representations (e.g., trajectories).

In short, all these couplings generate entropy in a complex non-equilibrium dynamics. However, from such a perspective, any focus on "what you see

is what you get", i.e., in terms of observable distributions which are the results of these communications, is insufficient without due attention to the specification of the analytical categories which are used for the reconstruction. The hypothesized systems allow us to specify the expectations, but they remain virtual during the observable operation (cf. Giddens, 1984).

PARADIGMS AND PARADIGM-SHIFTS

Kuhn's (1962) paradigms are sociological hypotheses with respect to the evolution of the sciences as communication systems. Paradigms can be considered as self-organizing communication systems with a life-cycle: the paradigm delineates what can be communicated within it. However, since the delineation is in terms of the substance of the communications, the system also opens itself to whoever is able to communicate in these terms. The self-organizing system is (partially) decomposed and recomposed in each operation. But what is to be considered as relevant, i.e., what is communicated in these interactions and what not, is controlled by the communication system. Given a new update, the self-organizing system may have to be redefined in terms of its substance, and its history may have to be rewritten.

The paradigm itself is not able to write or rewrite its own history. Although social systems may have storage capacities, they have no central memory available for operations other than the distributed memories of actors. The social network is a virtual system that operates at the addresses of the actors involved. Therefore, each reconstruction with respect to the systems under study remains an empirical hypothesis ("a representation") by one or more local actors. Alternative hypotheses introduce uncertainty at the reconstructive level. When this uncertainty can be reflexively communicated with reference to the system(s) under study, there is sufficient complexity (since there is both a substantive and a reflexive selection, and thus an additional degree of freedom between them) for the possibility of self-organization in this communication system.

Actually, the concept of paradigms has provided the sociology of science – and other fields (cf., Prigogine and Stengers, 1979/1984; Luhmann 1984) – with a mental model for understanding self-organizing social systems at the supra-individual level (cf. Leydesdorff, 1993a). It has allowed for the development of a relevant semantics in the sociology of scientific knowledge, but only with hindsight can one understand this enterprise reflexively as the emergence of a new hyper-cycle of scientific communication (Luhmann, 1990).

A *paradigm-shift* can be considered as a fundamental reorganization of the combination of eigen-structure and eigen-time of the system (in the reconstruction), so that what previously could only be understood as anomalies can henceforth be reintegrated into it. In other words, the nature of communication, i.e., what is expected to be communicable within the

communication system, shifts. Kuhn (1962) has noted this as “incommensurability” among paradigms: self-organizing systems differ among themselves in terms of what can be considered as communication. This is the case not only synchronically, but also diachronically: self-organizing systems may go through path-dependent transitions. Thereafter, they are expected to have changed in the nature of their communication. Since change has to be produced locally, subsystems in differentiated systems (e.g., specialties in the sciences) may go through path-dependent transitions in one dimension while maintaining significant continuity in others. This opens the possibility of various intersecting discourses. Note that both participants and meta-theoretical analysts can only communicate about the system on the basis of their reconstructions; these reconstructions may partially overlap.

In other words: in each round of operation the self-organizing system (“the paradigm”) is confronted with a large surplus of information (“variation”) which is offered for processing at local nodes. Without such processing there can be no “selection” by, nor “stabilization” of the reconstructed system. Stabilization requires selection with reference to the history of the system under reconstruction. In order to maintain identity, the static and the dynamic selection have to operate on one another. A scientific paradigm, for example, is expected to contain both selection mechanisms: in the limiting case, new evidence can be countered by an *ad hoc* hypothesis that is otherwise unrelated to the historical organization of uncertainty in the discipline, or in the other extreme the new evidence can be “counter-factually” disregarded as an anomaly (“noise”) by means of an appeal to the stabilized “hard core” of an existing body of theories (cf. Lakatos, 1970). Only if a specific trade-off between these two selections can be elaborated can the paradigm be strengthened as a theoretical system.

Keep in mind that all actions of the system have to be taken locally; hence, all reconstructions contain uncertainty that can be socially negotiated. The systems do not exist otherwise than as expectations with reference to distributions, and thus in terms of uncertainties. Since the systems are different with respect to *what* they communicate, the primary specification for the reflexive reconstruction is a theory about the systems in terms of the substance of their communications. The meta-theoretical analyst is reflexively aware of the reconstructed nature of the subject matter, while a participant may wish to build on his/her reconstruction for making an argument. Neither an analyst nor a participant, however, can abstract from content, but the meta-theoretical analyst has to formulate this hypothesis reflexively.

The specification of the systems at the meta-level enables the reflexive analyst to *position* the observable *relations* as action with reference to the relating units, *and* as communication in the hypothesized networks. Since the systems of reference have to remain empirical hypotheses, the networks under study remain uncertain, for example, in terms of their boundaries. But without a (possibly implicit) hypothesis, the relevant networks cannot

be specified categorically, and there can be no attempt to delimit them empirically. The question of whether a paradigm-shift has occurred or not can only be evaluated empirically with reference to the communication network, however uncertain it may be in terms of observables.

In terms of the so-called sociology of translation (e.g., Callon *et al.*, 1986), one may wish to formulate: which communications were linked into the actor-network, and how did they contribute to the translation? Indeed, the systems are composite outcomes of processes of deconstruction and reconstruction ("association") among heterogeneous units ("actants"), but the actor-networks conditionalize their own dynamics. (Latour (1988) has called the latter operation "attribution".) Since the systems under study contain information in the time dimension, the historical construction is at the same time a *reconstruction*. Note that even emergence can only be specified with reference to previously existing networks.

When studying the history of social networks, one should never equate the uncertainty in the constructed network with the sum of the uncertainties in the constructing units that are observed. First, one expects interaction terms that have to be attributed to the network. Secondly, not only the analysts reconstruct the networks under study, but also (some of) the actors under study are able to do so. Reflexive actors are expected to contain more uncertainty than their representations ("actants") in the network. As noted, the representations of the actors in the network are equal only to the mutual information in the window between the actors and the network. The network is selective with respect to the variations produced by the actors, since it is able to transmit messages only in its specific medium.⁶

The incoming information in the first dimension of a communication is positioned by the transmitting system using the second dimension of the network's extension. The information in the message has to be reconstructed by receiving actors who have then to perform a second selection. If these reconstructions are again communicated, a reflexive dimension is added to the *communication network* that was already two-dimensional. Note that the network is then potentially three-dimensional at each moment in time, and thus able to redirect or to translate input into output. The addition of the time dimension to this complex creates a four-dimensional system that operates in a hyper-space. The development of this system can no longer be fully reconstructed using geometrical metaphors; one needs algorithmic simulations for this reconstruction (Andersen, 1994).

In summary, by specifying the sciences in terms of reflexive communication systems that can exhibit evolutionary life-cycles, the sociology of scientific knowledge has provided us with a mental model for the reformulation of sociology as a positive science about social communication systems. Since the social system is a distributed system without central memory, one can only gain access to it through the reconstruction at one's local node. Participants and analysts can communicate about their reconstructions, but in potentially different layers of reflexive communications. Reflexivity in

the communications provides the network with sufficient complexity for allowing various operations of eigen-frequencies on eigen-vectors of the communication network. If a self-organizing paradigm or a regime (Dosi, 1982) emerges, the uncoupling of control in this system from the generating institutional structures and localized actors is a possibility, since self-organization is based on changing *network properties* (Leydesdorff, 1993b).

As noted, the needed "gestalt switch" requires the reader to combine Luhmann's (1984) understanding of society as an "autopoietic" communication system science is subsequently defined as a functionally differentiated subsystem of society – with Shannon's (1948) decision to take probabilistic entropy as the single fundamental concept. Luhmann's distinction of society from (aggregate of) actors enables us to objectify the study of social phenomenon. The parsimony in Shannon's definitions has enabled us to integrate the systems theoretical notion of probabilistic entropy with the sociological notion of variance and the theoretically important notion of scientific expectations.

The combination of this objectivation and mathematization provides us with theoretical guidance and a methodological warrant for empirical research. For example, one expects a self-organizing science system to be able to balance theoretical uncertainty against social variation within certain margins. The specification of the mechanisms in these translations is an empirical task. As noted, the development of communication systems is content specific, but content is not the only relevant dimension. Case studies can teach us relevant dimensions, and thereby inform our hypothesis with respect to possible selections and translations.

RELEVANCE FOR THE SOCIOLOGY OF SCIENTIFIC KNOWLEDGE

While in more traditional sociologies and philosophies of science the social and the cognitive were conceptualized as separate domains (e.g., "the context of discovery" and "the context of justification"), the post-Kuhnian paradigm has emphasized the indivisibility of "socio-cognitive action". The new line of research has focused on the dynamic development of the interaction between cognitive and the social; for example, in "socio-cognitive practices" (see, e.g., Pickering, 1992).

However, if one is reflexively aware that the outcome of interaction is again a complex which can be analyzed in terms of the various dimensions involved, then one must assume that in each instance the complex has changed in some respects, but may have remained the same in others. Subsequently, one is in need of a model to attribute the observed changes to the various dimensions and/or their interaction. In terms of methods, this problem can be formulated as the problem of combining the multi-variate perspective (e.g., of the relations between the research group *and* the scientific field in cognitive *and* social terms) with the dynamic perspective.

The study of the relations between multi-variate data-structures and

dynamic developments is not a sinecure. The time dimension adds a specific variate to the multi-variate complex: methodologically, it introduces auto-correlation in the observations, and theoretically, this auto-correlation in the data refers to self-referentiality in the systems that generated the variations under study (Leydesdorff, 1991). In other words, some complex data structures are reproduced during the operation, and in this case the resulting structures refer back to their previous state(s). However, whether or not distributions will develop as systems remains an empirical question in each instance.

Given the then unsolved methodological problems of how to attribute the observed data to the communication systems involved and/or their interactions, researchers in science studies had to make programmatic assumptions. Although results based on such assumptions may highlight important theoretical aspects, a mathematical sociology of scientific communication enables us to reflect on the value of these results with hindsight.

For example, if one wishes, as some micro-constructivists or post-modernists do, to deconstruct all structure in terms of actions or interactions, one has to assume that all structure is only a result of (inter)-actions *during the period under study*. In other words, the analysis in terms of contingent relations among actors (i.e., lower-level units) does not deconstruct all structure, but only that part of structure which is decomposable in terms of relations among actors within the relevant time horizon. If, given this time span, structure is partially self-referential, i.e., refers to itself at a previous moment, the micro-constructivist will be able to explain only the interaction terms between actors and structure within this time span.⁷

The history of the system under study never begins *de novo* during a period under study. As noted, even the emergence of a newly constructed system can only be specified historically with reference to previously existing networks. The eigen-vectors of the network of relations are latent dimensions which condition ("enable and constrain") action, but cannot be decomposed in terms of relations. In other words, the analysis of the observed distributions in terms of *relations* – as pursued by the constructivists – cannot be used for the study of *positions* with reference to the (sometimes implicitly) assumed systems under study (cf. Burt, 1982). The programmatic assumption in the relational or micro-constructivist programme is therefore self-defeating: in empirical research the micro-constructivist is no longer able to distinguish the extent to which action and structure are each other's determinants, or only each other's enabling and constraining conditions (Giddens, 1979 and 1984). The distinction between aggregated relations and positions with reference to latent dimensions of the network has not been sufficiently reflected in this tradition. I return to this distinction below, but let me first point to a related issue.

The strong programme in the sociology of scientific knowledge has wished to explain all cognitive variation in terms of its socio-cognitive construction. But is it feasible to explain cognitive variation in terms of socio-cognitive

variation? Slezak (1989, at pp. 588f.) noted that it makes no sense to explain a larger variance in terms of a smaller one. The programmatic assumption that the cognitive uncertainty in science is contained within the socio-cognitive interaction, and would thus be explainable in sociological terms, implies a highly unlikely answer to an empirical question on *a priori* grounds.

In science studies, this programmatic assumption has been introduced by Bloor (1976, pp. 40ff.) with reference to Durkheim's analysis of the forms of religious life. Indeed, the thesis that the sciences sometimes function as belief systems can be empirically fruitful (e.g., in controversy studies), but it does not prove that the sciences are not also different from belief systems in important respects. The analogy misses the point that as a scientist, one is free to theorize in modern societies, i.e., that the sciences, unlike normatively integrated forms of religious life, can also be considered as functionally differentiated subsystems. For example, someone's disbelief in a scientific "truth" no longer necessarily creates a schism between two religious communities, as in the Middle Ages; nowadays it often raises only a variety of further research questions. Thus, the mechanism for the communication of uncertainty is different. Modern sciences are not hierarchically organized belief systems, but at least to a certain degree, also juxtaposed discursive constructions.

"Belief" refers to an actor who expects something to be true. However, the sciences have been socially constructed as *discursive systems of rationalized expectations* not only in terms of their daily operations as practices, but in a much more profound sense, i.e., in their relation to society at large, and notably with reference to religious systems. At various places, Weber, Parsons, Merton, and Luhmann noted the importance of Protestant values for the emergence of modernity in general, and the differentiation of science in particular.

How is one to understand the thesis of functional differentiation in relation to "the Durkheimian programme" in the sociology of scientific knowledge? In contrast to theoretical expectations, a belief system must be normatively integrated and hierarchically organized. It can be attributed to a community of people (e.g., a church). In Catholicism, this "hierarchy" refers to the organization of the church,⁸ since the Pope is considered the Vicar of Christ. His Holiness is at the top of a *stratified* organization which covers the whole world ("kat' holèn gèn"). In Protestantism, each individual is equal before God, and therefore the world is given to people as a *latent structure in their network of relations*. By consequence, truth in scientific theorizing, the prices on the market, love in personal relations, etc., can become functionally differentiated from normative integration into individual or collective systems. Truth, for example, can become a potentially delocalized network function.

Once set free from normative control at the top of the hierarchy, the lower-level units, by relating in networks, can constitute heterarchical communication systems with their own dynamics.⁹ The problem of "science

and society" is subsequently so complex since it is the result of two problems, viz. the sociological question about the dynamic relations between individuals and society (social action and social structure), and the epistemological question about the relations between the knowing subject and the sciences as cognitive communication structure. "Socio-cognitive" communications contain substance and reflexivity, and thus the observed data can be attributed to more than one dimension of the differentiated system. Consequently, there is reconstructive flexibility in the attribution over the social and the cognitive contexts (cf. Hesse, 1980). The "socio-cognitive (inter-)action" of the scientists under study operationally couples two communication systems (e.g., their "social" group and their "cognitive" field) in one operation. But the social system cannot operate without actors contingently doing so, and thus the scientists involved are structurally coupled to the socio-cognitive communication in both dimensions. If the social system under study is differentiated, each action has therefore at least four meanings: one has to cross table actor(s) and communication networks as systems of reference versus the dimensions of differentiation in order to explain the interaction as a result.

Additionally, the update frequencies in the time dimension have to be specified. Both the research group and the scientific field are part of the larger social system. In a hyper-cycle the various cycles, i.e., the one of the individual and society, and the one of the knowing subject and scientific truth, can be integrated into one (super-)system, but with potentially different frequencies. The self-organizing (sub-)systems are at a next level the units for a second-order cybernetics which reproduces their differentiation, and thereby also secures the integrity of the lowest-level units (cf. Maturana and Varela, 1980; Simon, 1973). Historically, the semantics for this configuration have been shaped by the Protestant demand for freedom of religion; systematically, the internal processing of meaning in juxtaposed systems is crucial. Note that the specific form of the differentiation is also historically contingent, and thus subject to evolutionary change (cf. Teubner, 1987).

RELEVANCE FOR THE SOCIOLOGY OF TRANSLATION

The integrity of lower-level units was propounded in science studies by representatives of the sociology of translation, or the actor-network approach. It was extended beyond the domain of human beings: "non-humans" such as electrons, scallops, and texts, may equally be related to the actor-network as "actants" (see, e.g., Callon and Latour, 1981; Callon *et al.*, 1983; Latour, 1987a). In the sociology of translation, all heterogeneity is engineered into an actor-network by relations (Callon and Law, 1982; Callon *et al.*, 1983). The resulting (semiotic) network contains nothing but relations ("associations"); on the basis of this programmatic assumption there is simply no room left to discuss positions. Correspondingly, Latour's "macro-

actor" is not an "eigen-vector" or a "density" in the network, but an identifiable "translator" (e.g., "The Prince" in Latour (1987b)) who relates hierarchically to all the units involved. Analogously, the "macro-term" in the co-word network is a star in a graph, and not only an abstract position in a multi-dimensional space (cf. Callon *et al.*, 1989; Courtial, 1989). The relational algorithm which was used for the reconstruction does not allow for positional analysis.¹⁰

This lack of options to specify heterogeneity in terms of hypothetical factors deprives the analyst of the possibility of distinguishing among causes for events in the network, and *a fortiori* of distinguishing between causes and reasons (of actors!) with reference to these events. Consequently, Latour (1987a) can no longer decide whether Galilei was condemned because of a social failure or a cognitive error, or whether Lysenko was celebrated for his theoretical contributions or his ideological commitments (cf. Amsterdamska, 1990). Again, the programmatic assumption has become counter-productive: the assumed unity of the network, which seemed fruitful for its dynamic analysis – since it projected the multi-dimensionality in the construct on the single dimension of associations along the time axis – prohibits with hindsight the systematic distinction of aspects in which the network changed from those which remained the same. Correspondingly, the relational algorithm used in co-word programmes (e.g., LEXIMAPPE and CANDIDE) signals change, but it cannot find continuities (cf. Leydesdorff, 1992c).

One should keep firmly in sight that a network has an architecture, and that this architecture can be represented in terms of an eigen-structure at each moment in time. The implied structure makes it possible for the actors involved, among other things, to distinguish more clearly between experience and action. Receptive experience is dependent upon one's position, and the reflexive attribution of meaning to the incoming signal remains internal and discretionary to the actor who experiences and reflects. The "actor" generates uncertainty according to a different programme from that followed by the "actant", i.e. its subsequent representation in the communication network. The representations provide us with network addresses, but not with sufficient information to infer whether the represented units are reflexive agents or not. The reconstructive analyst needs to add this information as an hypothesis. This distinction between reflexive agents and irreflexive "actants" should be crucial for the sociology of translation, since without reflexive agents the network would not be able to maintain the additional dimension that is needed for the translation (see above and note 4).

The distinction between perception and reflexivity which remain discretionary to the actors, and observable communications in a network, is also a prerequisite for the understanding of what "truth" means in social communications. The reflexive processing of meaning by each of us according to our internal programme belongs to our heritage from the individualistic, and among other things "scientific", revolution – whatever

form this differentiation may take today. If, for programmatic reasons, one wishes to focus only on externally observable actions, without the specification of the various systems of expectations for which these actions are relevant events, one is no longer able to distinguish between internal processing (including the reflexive attribution of a truth-value to an information) within a system and its external effects (e.g., performance or economic success); and thus one deprives oneself *a priori* of the possibility of inspecting uncertainties in the truth and objectivity of scientific knowledge itself other than in terms of representations or measurable proxies (e.g., reputations).

Paradoxically, therefore, while Bloor (1976, p. 1) stated that "(t)here are no limitations which lie in the absolute or transcendent character of scientific knowledge itself, or in the special nature of rationality, validity, truth or objectivity", he proceeded to deprive himself of the possibility of giving an explanation of these concepts by insisting on their operationalization exclusively in terms of observable "socio-cognitive actions". He, and others who followed him in this respect, identified the unit of observation with the unit of analysis. Bloor was right that there is no need for the assumption of an absolute or transcendent character of scientific knowledge; self-referential and interactive processing of sociological and psychological meaning may or may not generate, for example, "truth" as a function of the scientific communication. However, these are not symmetrical operations, since the actor's actions and beliefs can make a difference in *other* dimensions. For example, it matters for the development of the discourse at the level of the network *what* the actors believe (cf. Mulkay *et al.*, 1983). The specification of these interactions requires a richer model than *a priori* assumptions about symmetry allow for.

In summary, "rationality, validity, truth or objectivity" are attributes of specific interactions between the different self-referential systems involved. No scientific truth can be communicated without reflexive scientists contingently doing so; without a message in a medium (e.g., a text or a discourse) which is codified enough to communicate this complex information; without a cognitive structure (e.g., a theory) which is sufficiently differentiated so that, among other things, the truth of the message can be distinguished from its information value. The analyst should *not* take the manifest "socio-cognitive action" as a unit of analysis or at face-value. The "socio-cognitive actions" should themselves be deconstructed as the events in which the social and the cognitive dimensions co-vary with reference to both the actors involved and the relevant (differentiated) networks. Two structurally coupled systems, the scientific agent and the scientific discourse, couple operationally in a single communication, but in various dimensions.

Analogously, scientometricians should not take words or citations by themselves as units of analysis and at face-value. Words are the prime examples of nominal variables; variables are necessarily attributes of a unit of analysis; and therefore, variables have meaning only with reference to

this unit of analysis. For example, words have no meaning except in the context of a sentence (Bar-Hillel, 1955). Changes in word-patterns are only the observable outcomes of various processes of change which may have taken place in the systems indicated by them. For example, while in a given scientific text one may find amazingly consistent word patterns, between two texts changes in word patterns may indicate substantive and/or semantic changes. The specification of these dimensions, and of whether change is expected to occur in them stochastically or systematically, may lead to different expectations for their occurrences in subsequent operations.

SUMMARY AND CONCLUSIONS

The programme, as formulated above, seems to share with the programme of logical positivism the feature that a model of science from the natural sciences is generalized to the social sciences. However, this is not the case: logical positivism specified a normative model in order to achieve a basis for ruling out categories of statements as meaningless, and to guarantee increasing certainty about the truth-likelihood of the other statements.

Because of their emphasis on constructivism, the sociology of scientific knowledge and the sociology of translation have provided us with a semantics for studying the sciences reflexively, as discourses and in terms of historically changing networks. But the sociology of scientific knowledge eventually shied away from the attribution of reflexivity to the network (e.g., Woolgar, 1988; Collins and Yearly, 1992), and the sociology of translation postulated that the network could be translated without any theoretical distinctions between reflexive actors who are (sometimes) able to represent themselves actively, and "actants" which are represented passively.

By specifying the various contexts of the observable events in terms of hypothetical systems of reference, an empirical and analytical programme for science studies emerges. Communications delineate the (sub-)systems, and one should not reason the other way round. Complexes (which may or may not be systematic) develop in relation to one another over time. To the extent that these developments condition one another, they create relevant uncertainty for each other. The generated uncertainty has to be coped with by all the systems for which this information is communicated, and by each system recursively. Additionally, by repeating relations over time, the systems may compose new systems: evolution has to be considered as a consequence of the potentially self-organizing development of complex communication systems. As the composite begins to behave autopoietically, control is increasingly top-down.

Our reflexive understanding of the science studies enterprise enlightens with hindsight our understanding of the sciences. When a self-organizing system can no longer contain the information, it must either be reorganized or give way to other forms of communication. Kuhn (1962) introduced the notions of paradigm and paradigm shift precisely to explain this

phenomenon: paradigms do not disappear, they just die out because they can no longer organize the information which is communicated when the system operates. Other combinations of structure and time can be used in order to reorganize the information content into another identity. However, this transition also changes the definition of what will count as information, and therefore the boundaries of the system in terms of contributing units will have to be redefined. Note that these definitions of information, communication, system and self-organization are content free, and may therefore include, among other things, the substantive knowledge content (e.g., what will count as a theoretical contribution) and the reflexive truth-likeness of the information.¹¹

The theory of potential self-organization in entropical systems provides the sociology of scientific knowledge with theoretical guidance, and in this context the mathematical theory of communication can provide a methodological warrant for theoretical inferences. Although this conclusion was drawn on the basis of an analysis of scientific communications, it seems valuable for all relations between dynamic systems. Systems couple at various levels of aggregation and in a variety of dimensions. On the one hand, one has always to specify the dynamics under study in empirical research. For example, one can study the cognitive coupling between results of scientific research and scientific theory in terms of statements, knowledge claims and theories, but the study of the coupling between research groups and scientific theories requires the additional specification of individuals or groups of actors who are expected to understand the relevant theories, and who are able and willing to communicate with relevant colleagues about them.

On the other hand, the complexity and the uniqueness of history refers to the complexity and the non-linearity of the different systems involved. Using mathematical means, one is able to generalize on the basis of the various specifications, and sometimes to explicate the expectation for subsequent testing. The uncertainty in the expectation provides us with a reflexive starting point for theorizing. At the philosophical level, the understanding of the sciences in terms of conditionalized ranges of options may help to shield against historicism on the one hand, and prescriptive methodologies on the other.

NOTES

¹ This decision has been vigorously debated in the literature. The concept of information as *uncertainty* is semantically counter-intuitive (cf. Bailey, 1990). Some authors have, therefore, made an argument for defining information as the negative difference in the entropy of the observing system ("negentropy", Brillouin, 1962). However, one has to distinguish between *expected* information (defined as uncertainty) and *observed* information that has to be positioned or given meaning with reference to an observing system. While this discussion has led to differences in semantic interpretation, it has not really affected the conceptual issues (cf. Hayles, 1990).

² Although differently defined, the variance and the expected information content of a distribution can both be considered as measures of the uncertainty. Analogously, the concept co-variance is equivalent to the mutual information (Theil, 1972).

³ 'Within this interpretation "paradigm" is taken to be a term which emphasises the combined *socio-cognitive* nature of scientific activity.' (Pinch, 1982, p. 17).

⁴ Variation in an incoming signal can be selected in a second dimension. In a three-dimensional system, selection can be made recursive, and the system gains reflexivity in a second order cybernetics, i.e., it has the potential not only to transmit, but also to redirect the information. For maintaining identity, a system needs additionally to be able to select reflexively among possible translations.

⁵ It can be shown that the expected information value of the update may have a negative sign for a reflexive communication system (Brillouin, 1962; Bailey, 1990; Leydesdorff, 1992a).

⁶ If the system was in each iteration deconstructable as a sum of (hierarchical) relations among "actants", it would not be able to maintain its self-organizing character as a specific selection (i.e., grouping) and stabilization of the probabilistic entropy.

⁷ Knorr-Cetina (1981: 27) argued that "unlike the natural sciences the social sciences cannot hope to get to know the macro-order conceived in terms of emergent properties: they are methodologically bound to draw upon member's knowledge and accounts, yet ramifications of unintended consequences by definition cannot be part of social knowledge". However, this typification of the natural sciences is flawed, and the argument oversees that a reflexive analyst can develop an hypothesis that is not (yet) available to the participant.

⁸ The word "hierarchy" is derived from the Greek words "hieros" and "archein" which respectively mean "holy" and "reign".

⁹ Independently of whether or not the individual units are composed hierarchically (e.g., normatively controlled by their "super-ego"), they may function heterarchically with reference to the network (cf. Parsons, 1952).

¹⁰ Callon (1990) allowed for institutional differentiation between "poles" in the network. However, this differentiation is "given" for the network, and not conceptualized in relation to it. In another study, Latour (1991) advocated de-differentiation as the main programmatic message of this sociology to political philosophy.

¹¹ The truth-likelihood of a scientific statement can be considered as a second dimension of the expected information content of the message (Leydesdorff, 1990).

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