



Organization Science

Publication details, including instructions for authors and subscription information:
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To cite this article:

Kenneth A. Frank, Kyle Fahrbach, (1999) Organization Culture as a Complex System: Balance and Information in Models of Influence and Selection. *Organization Science* 10(3):253-277. <http://dx.doi.org/10.1287/orsc.10.3.253>

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Organization Culture as a Complex System: Balance and Information in Models of Influence and Selection

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Abstract

We define the complex system underlying organizational culture by incorporating the social-psychological principles of balance and information (B-I) into models of influence (changes in attitudes as a function of interaction) and selection (changes in interaction). We identify information based influence as a potential anchor for actors' sentiments so that they are not overwhelmed by normative influence. In the model of selection, we identify the pursuit of information as an important counterbalance to the effect of homophily (interacting with others like oneself). Using the tools of dynamic systems we show how our models generate the full range of equilibria of complex systems. Through simulations we also explore how our system responds to exogenous effects.

(Complexity in Organizations; Interpersonal Influence; Selection Models; Simulation)

Introduction: What Makes An Organization A Complex System?

Even if we take as given that organizations are complex systems (Carley 1995, Stacey 1996, Thietart and Forgues 1995), in this article we ask "What makes an organization a complex system?" To describe organizations as complex (and chaotic) systems we should be able to demonstrate that they feature three types of equilibria (Alligood, et al., 1996, Stacey 1996, Stewart 1989, Thietart and Forgues 1995). The first is an explosive situation caused by positive feedback in the system. In the second form of equilibrium the organizational structure quickly returns to a stable state even after the introduction of fairly large shocks to the system. Finally, and most interestingly for most systems, when there are counteracting influences involving positive and negative feedback, the system may approach a state in which the system continually changes, but the structure is bounded and has periodic stability.

Each form of equilibrium can be induced by exogenous effects (Cohen et al. 1972, Stacey 1996, Thompson 1967, Woodward 1965). In light of these inputs, the organization is itself changing in complex, unpredictable ways. But if this conceptualization dominates, the boundaries of the organizations are extremely open to the point of being indiscernible. In these circumstances it is difficult to predict organizational structures and to understand organizational decision making, as the organization is awash with the effects of the exogenous effects.

In this article we will develop models of the intra-organizational processes through which actors' interactions and sentiments (values, attitudes, beliefs, opinions, etc.)¹ become interrelated, and we will show that the system they define is complex. In particular, we will combine balance theory and information theory to specify models of influence (changes in actors' sentiments as a function of interaction) and selection (changes in the pattern of interaction as a function of actors' sentiments). These processes define the core elements of organizational culture. But while the processes are internal to an organization, they are dependent on the assumption that actors are exposed to exogenous shocks to the system. Thus we roughly characterize the processes through which organizational members shape organizational culture as they transmit exogenous effects to the organization.

In the next section we characterize the basic processes through which actors construct and are influenced by the pattern of interaction and the distribution of sentiment. We then develop formal models of each process incorporating balance and information theories. As we do so, we use the tools of dynamic systems to demonstrate how the combination of information and balance generates the full range of equilibria of complex systems. We then explore how our system responds to exogenous effects. In the last section we draw some conclusions and identify possible extensions, emphasizing how actors construct and reconstruct organizational cultures as well as form

the medium through which exogenous effects permeate the organizational boundary.

Processes Defining Organizational Culture

Barnard (1961) provides a basis for defining organizations as a particular form of a system:

A cooperative system is a complex of physical, biological, personal and social components which are in a specific systematic relationship by reason of the cooperation of two or more persons for at least one definite end. Such a system is evidently a subordinate unit of larger systems from one point of view; and itself embraces subsidiary systems—physical, biological, etc.—from another point of view. One of the systems comprised within a cooperative system, the one which is implicit in the phrase “cooperation of two or more persons” is called an ‘organization’ (p. 14).

Note that Barnard emphasizes that a critical aspect of systems in general, and organizations in particular, is the cooperation between persons. Enduring cooperation can occur only if actors engage in some form of communication that changes some attribute of the actors, either their beliefs, sentiments, or behaviors (Durkheim 1976, Parsons and Shils 1954, Simon 1965). Thus we will focus on two defining aspects of organizations—interactions among individuals (Alexander 1987, Collins 1981, Durkheim 1976, Merton 1957, Parsons and Shils 1954, Turner 1988, Weber 1958) and sentiments or behaviors that are affected by interactions (Coleman 1986, Durkheim 1976, Goffman 1959, Mead 1962, Parsons 1951, Turner 1988). Correspondingly, we focus less on the structure of the formal organization that affects the sharing of immediately relevant information affecting productivity (Davis and Lawrence 1977, Lin and Carley 1995, Radner 1992, Roberts 1989) and more on the structure of the informal organization that affects the pattern of interaction through which actors influence one another’s sentiments.

The causes and consequences of interaction are the core of organizational culture (Cushman 1977, Pacanowsky and O’Donnell-Trujillo 1982, Schall 1983, Spradley 1979). The sentiments that change as a result of communication can accumulate into an organizational ethos such as one of caring, bureaucracy, or entropy. The pattern of interaction itself can be indicative of organizational culture, to the extent that interactions are hierarchical, concentrated within cohesive subgroups, or randomly distributed. Thus, for some, the pattern of communication *defines* the culture of an organization (Hall 1959).

While organizational culture has only tentatively been

linked with organizational productivity (Kotter and Heskett 1992, Siehl and Martin 1990), culture affects processes of reorganization and adaptation that ultimately affect productivity. For example, fluid cultures that afford opportunities to share information and opinions may help an organization to adapt to external changes more quickly than other cultures (Caldwell and O’Reilly 1995, Nemeth and Staw 1989). Thus the processes associated with the pattern of interaction among organizational members represent the geological forces that shape the landscape on which organizational productivity is built.

Though we describe the formation of culture as “geological,” it is the product of individual level action. For example, O’Reilly and Chatman (1996) comment that organizational culture “can be thought of as the normative order, operating through informational and social influence, that guides and constrains the *behavior of people* in collectives” (p. 160, emphasis added). *Organizations* do not decide to become bureaucratic. Bureaucracy, or any other organizational form, is the function of the actions of people in the organization, perhaps in response to conditions outside the organization (e.g., March and Olsen 1976, Macdonald 1995). Thus in exploring the processes that generate organizational culture, we will develop models at the individual level. But while the models are defined at the level of the individual or pair of individuals, the parameters that govern the processes generally characterize the organization. Thus it is the parameters, and the way they govern the distribution of sentiment and the pattern of interaction, that define organizational culture.

There are two general streams of literature on which one can draw to generate models of the causes and consequences of actors’ interactions. There is an economic model in which actors seek to maximize their own utility (Dosi 1995, Williamson 1985, 1995) or exogenously defined preferences (Jacoby 1990), and the organization is defined by its ability to coordinate action (Marschak and Radner 1972, Williamson, 1991). Even when actors share preferences such as in teams (Lin and Carley 1992, Marschak and Radner 1972), the models are economic in the sense that actors seek to maximize productivity and their access to resources. Alternatively, the interactions of actors may be considered from the social-psychological perspective, and the organization defined in terms of the pattern of actors’ interactions and distribution of sentiment (Alexander 1987, Durkheim 1976, Giddens 1984, Goffman 1959, Kaufer and Carley 1993, Parsons and Shils 1954, Turner 1988).

Of course, each model can be cast in the others’ framework because the social-psychological motivations that generate actors’ actions can be characterized in terms of maximization of utility (e.g., DeVree and Dagavos 1994).

When one's focus is on the pursuit of common resources, the economic perspective may be more informative, whereas when one's focus is on resources that cannot be valued and exchanged across an organization, the social-psychological theories may be more applicable. In this article our focus is on the construction of organizational culture, which is not directly a function of competition for resources. Correspondingly, we build our models on social-psychological principles.

We will draw on two fundamental principles of social psychology that link actors' interactions and their sentiments. First, actors seek balance (Davis 1967, Heider 1958, Newcomb 1961) that they may achieve either by modifying their sentiments to correspond to others around them (e.g., Festinger 1950, Steiner 1966, Schachter 1951), or by choosing to interact with others who hold similar beliefs (Blau 1977, Durkheim 1976, Festinger et al. 1950, Heider 1958, Homans 1950, Marsden 1981, Newcomb 1961, Simmel 1955; see Byrne 1971, chapter 2 for a review). Second, actors' sentiments are affected by the information to which they are exposed through interaction with others (Anderson 1971, Hovland and Kelly 1953), and actors may choose to interact with others to gain access to new information (Miller and Jablin 1991, Morrison 1993, Reichers 1987, Rosen 1961). While balance and information are often considered competing processes, we will incorporate them side-by-side in formal models of influence and selection.² We refer to the system defined by our models as a balance and information (B-I) system.

In general, our models allow us to explore how organizational culture emerges from social-psychological processes at the level of the individual and the dyad (Alexander 1987, Coleman 1986, Dewey 1958, Durkheim 1976, Giddens 1984, Parsons and Shils 1954, Turner 1988), an approach sometimes referred to as methodological individualism (Brodbeck 1958, Coleman 1986, Giddens 1984, Haines 1988). The approach takes the individual as an actor reacting to the influences of others, but also selecting those with whom to interact and who thus define the actor's context. This allows us to specify the dynamic processes through which individuals construct and reconstruct organizations, processes that cannot be explored through analyses at the organizational level (e.g., Cheng and Van de Ven 1996, Hannan and Ranger-Moore 1990, Stinchcombe 1965).

Through our models we also explore how organizational culture affects organizational response to exogenous effects (adaptation). This addresses a critical gap between studies of the internal processes of organizations (such as is typically conducted by social psychologists studying organizational behavior) and of organizational

response to external conditions (such as is typically conducted by sociologists of organizations or in the literature on business—see Krackhardt and Brass 1994). The study of internal organizational culture has often taken a managerial perspective on how to cultivate a particular type of culture to enhance performance, regardless of the exogenous effects on the organization (Chandler 1962, Charters 1973, Cyert and March 1963, Etzioni 1961, March and Simon 1958). But sociological perspectives such as contingency theory (Lawrence and Lorsch 1967, Thompson 1967, Woodward 1965) and open systems theory (Berman 1978, Bidwell and Kasarda 1987, Katz and Kahn 1978, Pfeffer and Salancik 1978) have questioned the ability of a single or small set of actors to direct an organization. Instead, organizations are conceived of as generally reacting to their external conditions.

While theories of the organization have long recognized that the internal culture of the organization also affects organization response, recently the new institutionalists (e.g., DiMaggio and Powell 1991, Meyer and Rowan 1977, Zucker 1988) have described how organizational culture is itself responsive to external conditions. Drawing on implications from loose coupling, advocates of "The New Institutionalism" argue that many "decisions" in organizations are based on the accumulation of small changes in cognitions and schema (sentiments) of actors in the organization (DiMaggio and Powell 1991, Rowan 1995). Most importantly, these cognitive schema form in response to conditions external to the organization, as institutions external to an organization "penetrate the organization, creating the lenses through which actors view the world and the very categories of structure, action, and thought" (DiMaggio and Powell 1991, p. 13).

But while open systems theorists and the new institutionalists have rightly focused our attention on the general permeability of the organizational boundary, they do not extensively address the mechanisms through which actors translate effects external to the organization into changes within the organization. Discussions of these processes either imply a return to control theory in which a few key actors mediate between the organization and the external environment (Katz and Kahn 1978), fall back on characterization of the organization as the unit (Bidwell and Kasarda 1987, DiMaggio and Powell 1991, Meyer and Rowan 1977, Pfeffer and Salancik 1978, Zucker 1988), or alternate between individual and organization levels of analysis (Astley and Van de Ven 1983). The limitation is not in the conceptualization of the relationship between the organization and its environment, but in the conceptualization of processes through which the organizational boundary is permeated.

By modeling intraorganizational processes at the level

of the individual, we can identify the role that each individual plays in generating organizational culture and in mediating between exogenous influences and the internal organization.³ In this sense, each individual potentially functions as a gatekeeper (Allen 1966, Gruber and Marquis 1969, Macdonald 1995) or a boundary pressure point (Abrahamson and Rosenkopf 1997) for organizational change. If organizations respond to external contingencies, who recognizes those contingencies, who formulates possible responses, who executes the response? If the organizational boundary can generally be permeated by external institutions, who is responsible for mediating the effect? And how are these processes affected by the internal structures of organizations? Do members of an organization equally and independently convey the effects of external institutions to their organization, or do a few convey the effect that is transmitted throughout the organization through the structures defining the organizational culture? The models we develop in this article will provide a glimpse into the processes related to such questions.

Substantively, throughout this article we will consider the example of the generation of school culture defined by the sentiments and interactions among teachers and administrators. In many ways the study of schools has paralleled or been representative of the general development of organizational theory (see Bidwell and Kas 1987, Bolman and Heller 1995, and Perrow 1986 for reviews), from control theory (Callahan 1962) to contingency theory (e.g., Greenfield 1975) and then the new institutionalism (Meyer and Rowan 1977, Rowan 1995). For an example of the latter, teachers' schema form the underlying bases for many practices, and thus influence the production process in the classroom; any "decisions" made by administrators must be responsive to the current practices and beliefs of many teachers in the school (Cleveland 1985, Fuller and Izu 1986, Rosenholtz 1989). Moreover, the context of schools allows us to focus on the processes associated with organizational culture. First, schools are bounded organizations. During the school day, we generally know the membership and location of the teachers, administrators, and staff of the school. Thus we can focus on the sentiments of school members and the interactions between them that define the school culture. Second, it is difficult to define the productivity of a school or of an individual teacher (Bidwell 1965). In this context, competition cannot be defined and schools have become monopolies (Crozier 1964, Rowan 1995, Michaelsen 1978). As monopolies, schools do not adapt to changing conditions through selection as described by niche theory (Bidwell and Kasarda 1987,

Hannan and Freeman 1984). Further, because the managers of schools—principals and administrators—cannot directly assess the productivity of faculty, they have relatively little formal control over others in the school (Lortie 1977, Meindl 1993). Therefore the organizational structure is essentially flat (Bidwell, 1965), and existing practices, sentiments, and patterns of interaction that typify the school culture have considerable effect on school decision making (Berger and Luckmann 1967, Bird and Little 1986, Purkey and Smith 1985, Reyes 1990, Rosenholtz 1989).

Methodologically, we will draw on the mathematical tools of dynamic systems to describe the processes we generate through our models of selection and influence. We begin by using differential equations to generally describe the continuous processes implied by basic models of influence or selection (e.g., Alligood et al. 1996). But as we incorporate components based on information and balance, our respecifications include discontinuities and nonlinearities that cannot be readily captured with the differential equations meant for continuous time dynamic processes. Therefore, like others (Carley 1995, Hillis 1992, Hummon 1990, Reynolds 1985), we turn to simulation studies to explore the organizational processes and structures generated by our models.

Models of Social Network Processes: Dynamic Systems in Organizations

In order to represent the processes through which organizational culture is generated we integrate two of the primary models used in social network analyses. First, most specifications of dynamic processes treat actors' sentiments or behaviors as outcomes, influenced by the others with whom they interact (Abelson and Bernstein 1976, Burt, 1987, Carley, 1989, Helbing, 1994, Friedkin and Marsden 1994), or treat actors' interactions as outcomes based on similarities in actors' sentiments or behaviors (Banks and Carley 1996, Iacobucci and Wasserman 1988, Leydesdorff 1991, Sanil et al. 1995, Snijders 1996, Zeggelink 1994, Zeggelink et al. 1996). Until recently, the models for each process were developed independently, without appreciation for the possibility of cointegration and codevelopment.⁴ But the two processes are inherently complementary, as actors interact with one another based on their sentiments, and sentiments are formed and reformed based on interactions (cf. Homans 1950). Recently, there have been a series of specifications of cointegrated dynamic models including social network processes as both predictor and outcome (Collins 1981, Carley 1990, 1991, DeVree and Dagavos 1994, Frank 1995, Leenders 1995, Stokman and

Zeggelink 1996). Only with these specifications is there the potential to represent the nonlinear dynamic processes we expect to observe in organizations.

The Model of Influence

A basic feature of most organizations is that actors influence one another through interaction, for example through face-to-face contact (e.g., Homans 1950, Festinger 1950, Mitchell 1973), written communication (e.g., Kaufer and Carley 1993) or e-mail exchanges (e.g., Freeman 1986). In schools, teachers interact to influence each other’s orientations towards teaching (Fuller and Izu 1986, Grant 1988, Hanson 1978, Lightfoot 1983, Rosenholtz and Simpson 1990, Zeichner and Gore 1989). This process can be represented through the model of influence through a social network (Doreian 1981, Friedkin and Johnsen 1990, Marsden and Friedkin 1994).

In order to write the model, define y_{it} to represent the sentiments of actor i at time t , and $k_{i'i'-1}$ to represent the extent of the interaction between i and i' . The influence of i' on i is then represented by $k_{i'i'-1} y_{i't-1}$, and the influence of all others on i by $\sum_{i' \neq i} k_{i'i'-1} y_{i't-1}$, the model of influence through a social network (see Marsden and Friedkin 1994, Equation (3) and for earlier references)⁵ is:

$$y_{it} = \alpha \sum_{i'=1}^N (k_{i'i'-1} y_{i't-1}). \tag{1}$$

In general, at time t , the sentiments of actor i are a function of the sentiments of the others with whom the actor engages in interaction.

Note that the influence of an actor upon itself is captured through the term k_{iit-1} . This effect can be parameterized and more explicitly represented in the following model:

$$y_{it} = \alpha \sum_{\substack{i'=1 \\ i' \neq i}}^{N-1} (k_{i'i'-1} y_{i't-1}) + \gamma y_{it-1}. \tag{2}$$

We can use Model (2) to represent theoretical arguments regarding how structures produce and reproduce themselves through the actions and internalizations of individual actors (DeVree and Dagavos 1994, Durkheim 1984, Giddens 1977, Parsons and Shils 1954). The larger the value of γ , the more actors retain their sentiment and the structure of sentiments, $\mathbf{Y}_t = (y_{1t}, y_{2t}, \dots, y_{nt})$, reproduces itself. On the other hand, the larger the value of α , the more actors are influenced by others, and the structure of sentiments is more dependent on the structure of interactions, $\mathbf{K}_t = (k_{12t}, k_{13t}, \dots, k_{nm-1t})$.

Before continuing, we explore the notation of $k_{i'i'}$. At the most micro level there may be no single time point at

which interaction occurs (Collins 1981, Dewey 1958, Turner 1988). Interaction between i and i' begins with an action of i that is perceived and internalized by i' . The interaction is fulfilled when i' then responds to the action of i in a way that i perceives. For example, in defining interaction, Stogdill (1959) wrote: “By interaction is meant that, in a system composed of two members, A reacts to B and B reacts to A in such a manner that the response of each is a reaction to the behavior of the other” (p. 18). Because interaction consists of multiple actions there is no single time point of interaction, and interactions may occur over variable intervals of time. Therefore it may not be accurate to refer to $k_{i'i't}$. Instead let $k_{i'i't-1 \rightarrow t}$ represent all interaction that occurs between i and i' from $t - 1$ to t . The model of influence is then:

$$y_{it} = \alpha \sum_{\substack{i'=1 \\ i' \neq i}}^{N-1} (k_{i'i't-1 \rightarrow t} y_{i't-1}) + \gamma y_{it-1}. \tag{3}$$

The units of t can be as short as the few seconds required for interaction in some experimental studies, or a few months over which meaningful interactions occur between members of an organization, such as between teachers in a school.

Given the specification of a deterministic system as in Model (3), we explore the properties of systemic behavior by employing the tools of complex systems (e.g., Alligood et al. 1996). To begin, we define the system for only two actors, **1** and **2**, as in (Duncan et al. 1968), and assume that $k_{12t-1 \rightarrow t} = k_{21t-1 \rightarrow t} = k$. That is interaction is symmetric and occurs at a constant rate across all time periods. We rewrite the system as:

$$\begin{aligned} y_{1t} &= \alpha k y_{2t-1} + \gamma y_{1t-1}, \\ y_{2t} &= \alpha k y_{1t-1} + \gamma y_{2t-1}. \end{aligned} \tag{4}$$

In Figure 1 we demonstrate the progression of values of y_1 and y_2 for a system in which the actors respond to each other’s sentiment, as in Model (3). The data were generated via simulation, with starting values of $y_1 = 1$ and $y_2 = -0.9$, $k = 1$, and parameter values of $\gamma = 1$, $\alpha = 0.1$. Subsequent values for each time point were generated from Model (4) (Alligood et al. 1996, Devaney 1990). The process can also be observed in the phase portrait in Figure 2 (see the technical appendix for the specification of our system in continuous time required to produce the phase portrait). The phase portrait is one of the early and unique tools used to represent complex systems. It allows one to show the continuous time relationship between two variables with time represented only in the directionality indicated by the arrows (Alligood et al. 1996; see Gleick 1987, pp. 49–51 for the

Figure 1 Trajectories of Sentiment When All Paths Are Operative

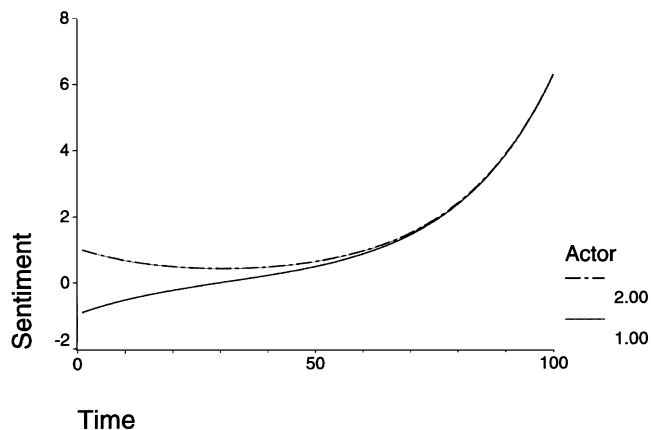
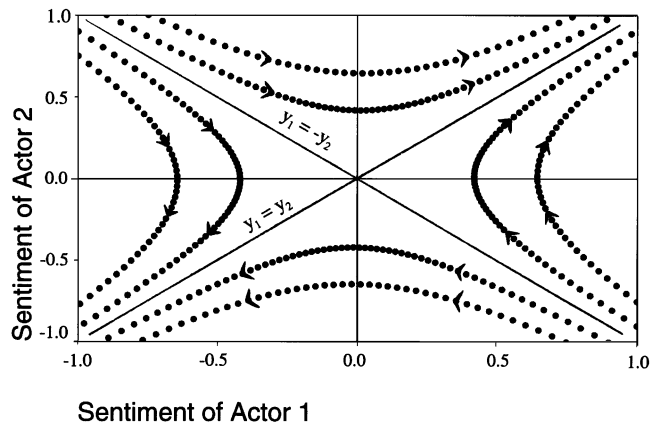


Figure 2 Convergence of System to the Line $y_1 = y_2$



development of phase portraits).⁶ In this case the multiple flows in the phase portrait reveal that the same equilibrium will be reached regardless of the starting conditions.

At one level, the processes represented in Figures 1 and 2 are quite sensible, suggesting that the two actors in the system will move towards agreement in sentiment. This is an equilibrium of a complex system, in which the system moves towards a specific state assuming there are no external shocks. And yet, there are several limitations to the system. First, the two actors move toward agreement in almost all cases. While we accept that in some circumstances two actors will come to agreement, surely there must be many in which they do not. In the present case, two actors will not come to agreement only if they begin with exactly opposite sentiments. That is, our representation of systemic processes is limited because the system that we generate is not sensitive to most initial conditions.

Second, a peculiar feature of Figure 1 is that although the actors move towards agreement, their sentiments explode towards extreme positive or negative values (depending on the sign of the mean sentiment at time zero). That is, if the actors started with original sentiments of -1 and 2 , their sentiments would eventually move to $(+\infty, +\infty)$. Although this result is implied by Asch's (1951) experiments and may occur naturally in the type of mob behavior that overwhelms the individual (Le Bon 1895, Moscovici 1981), it seems an unusual occurrence.

The problem of exploding sentiment can be addressed by a priori constraining the mean at each time point to be zero or a constant (Leenders 1995). Exploding sentiment is not a concern if the sentiment is specified as dichotomous (Carley 1989, Kaufer and Carley 1993, Stokman and Zeggelink 1996), as is the case in most analyses of the diffusion of an innovation, in which case the innovation is either adopted or not (Abrahamson and Rosenkopf 1997, Bartholomew 1973, Coleman 1964, Rogers 1995). But we wish to explore the conditions under which sentiments that define organizational culture explode or not, which we cannot do if the sentiments are constrained by a constant base or by the range on which they are measured.

Thus we return to Model (3) in which observe how the potential for explosion is produced by feedback in the model. Note that actor's sentiment at time $t - 1$ affects the sentiment of that actor *and potentially all other actors* in the system at time t . Thus each actor is influenced by the other's sentiments that themselves were functions of the prior sentiments of the two actors. As one actor's sentiment increases so too will the other's, until both approach $\pm\infty$.

To constrain the processes of influence, the sentiments of the actors must be anchored.⁷ For example, Friedkin and Johnsen (1990) anchor the sentiments at each time point to the sentiments predicted by a host of background characteristics of the individual at time zero, and Friedkin and Johnsen (1997) anchor each actor's sentiments at time t to the actor's sentiments at $t = 0$. The conception here is one of an individual being influenced through interaction with others, but retaining some of his or her initial sentiment. In the next subsection we extend Friedkin and Johnsen (1997) by drawing on social-psychological theories of influence to separate between information effects and normative effects. The anchor to the system is then defined by the information that has entered the system at any time.

Longitudinal and Informational Conceptualization of the Influence Model

There are two fundamental limitations to Model (3). First, it is based on an influence process whereby an actor is

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influenced by the *sentiments* of the other actors with whom he/she interacts. An alternative conceptualization builds on the notion of changes in sentiment as a result of exposure to information (Carley 1991, Coleman 1964, Kaufer and Carley 1993, Pfeffer 1982). Here the error terms of Model (3) represent facts that actors accumulate through interaction (Festinger et al. 1950, Garfinkel 1967, Granovetter 1974) and that affect their sentiments (Burnstein and Vinokur 1977, Carley 1990). For example, teachers may modify their attitudes regarding students with disabilities on the basis of information they obtain from other teachers (e.g., Houck and Rogers 1994, Pugach and Johnson 1989). In this context, the organizational culture represents the distribution of information (Cushman 1977, Hall 1959, Kaufer and Carley 1993, Leydesdorff 1991, Pacanowsky and O'Donnell-Trujillo 1982, Schall 1983, Spradley 1979), and organizations can be defined in terms of how they manage information (Arrow 1979, Cyert and March 1963, Galbraith 1973, Marschak and Radner 1972). In our example, schools may be characterized partly in terms of the distribution of the awareness of techniques for teaching students with disabilities (e.g., Fuchs et al. 1995, Jones and Guskin 1984).

Second, although Markovian models have been used to represent many phenomena accurately (Puterman 1994), there are Markovian-like assumptions within Model (3) that may not be applicable for organizational processes. Specifically, not only is the link from an actor to itself through γ reflective of a Markovian process, but so too are the sentiments of the others incorporated in the term $\sum_{i'} k_{ii't-1 \rightarrow t} y_{i't-1}$. Representing the influence of others based on the sentiments of the others at time $t - 1$ masks the processes through which the others' sentiments were themselves formed through exposure to information at earlier time points. To make this clear, we reconsider Model (3) from the perspective of information theory.

In the information, or learning theory model (e.g., Anderson 1971, Hovland and Kelly 1953) a person is influenced by a "fact" or piece of information when they are exposed to it, and their sentiment is a culmination of the facts to which they are exposed, regardless of the frequency of exposure. These facts can be represented as exogenous effects, e_{it} , that enter the system at any time. For example, a fact may enter the system when teacher i at time t learns of new legislation regarding the education of students with disabilities. We can then represent a general solution (Enders 1995) to Model (3) consisting of the chains of interactions connecting the exogenous effects to each actor (the chains are called paths: a path from actor i' at time $t-v$ to actor i at time t is a combination of

interactions linking actor i' at time $t-v$ to actor i at time t).

Let $\lambda_{i'} = \gamma$ if $i' = i$, and $\lambda_{i'} = \alpha$ if $i' \neq i$, thus allowing us to recombine effects of an actor upon itself and of others into one term. The information-based representation is:

$$\begin{aligned}
 y_{it} &= \sum_{i'=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} y_{i't-1} + e_{it} = \sum_{i'=1}^N \left[\lambda_{i'} k_{ii't-1 \rightarrow t} \left(\sum_{j=1}^N \lambda_{i'} k_{i'jt-2 \rightarrow t-1} y_{jt-2} + e_{i't-1} \right) \right] \\
 &+ e_{it} = \sum_{i'=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} e_{i't-1} \\
 &+ \left[\sum_{i'=1}^N \sum_{j=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} k_{i'jt-2 \rightarrow t-1} y_{jt-2} \right] + e_{it} \\
 &= \sum_{i'=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} e_{i't-1} + \left[\sum_{i'=1}^N \sum_{j=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} \right. \\
 &k_{i'jt-2 \rightarrow t-1} \left. \left(\sum_{m=1}^N \lambda_{i'} k_{jmt-3 \rightarrow t-2} y_{mt-3} + e_{mt-2} \right) \right] \\
 &+ e_{it} = \sum_{i'=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} e_{i't-1} + \sum_{i'=1}^N \sum_{j=1}^N \\
 &\lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} k_{i'jt-2 \rightarrow t-1} e_{jt-2} + \left[\sum_{i'=1}^N \sum_{j=1}^N \sum_{m=1}^N \right. \\
 &\lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} k_{i'jt-2 \rightarrow t-1} (\lambda_{i'} k_{jmt-3 \rightarrow t-2} y_{mt-3}) \left. \right] + e_{it} \\
 &= \vdots \\
 &= \sum_{i'=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} e_{i't-1} + \sum_{i'=1}^N \sum_{j=1}^N \lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} \\
 &k_{i'jt-2 \rightarrow t-1} e_{jt-2} + \dots + \sum_{j=1}^N \sum_{m=1}^N \dots \sum_{v=1}^N \\
 &\lambda_{i'} k_{ii't-1 \rightarrow t} \lambda_{i'} k_{i'jt-2 \rightarrow t-1} \dots \lambda_{i'} k_{i'v \rightarrow t-1} e_{v \rightarrow t} \quad (5)
 \end{aligned}$$

Model (5) reveals the limitation of Model (3) from the information perspective. In particular, we observe that each exogenous effect that entered the system prior to $t - 1$ has multiple effects on actor i that are transmitted through all possible paths linking to the actor who first experienced the effect. The exogenous effect experienced by actor i' at time $t-v$ can actually have a greater subsequent effect on actor i than on i' .⁸

There are many circumstances under which we do not need to account for effects of information that accumulate

throughout the network. For example, in exchange models (e.g., Blau 1967), actors transfer a resource to others through exchanges. Therefore, each time actor i' engages in an exchange, actor i' transfers some of the resources he might use to exchange with others. The quantity of the outcome is fixed (except for exogenous inputs) and therefore any component of the outcome cannot have repeated and multiple influences on others that accumulate throughout the system. In other words, because in an exchange model the values of $y_{i't}$ are themselves adjusted after each exchange, it is not as necessary to control for repeated effects a single actor may have on others through interpersonal influence.

But influence through information is not an exchange process. When one actor informs another, the total amount of information is increased in the system. It is this process that allows for an accumulation of effects that can produce an explosion in sentiment. Therefore we may wish to limit the extent to which a single exogenous effect can have cumulative effects on actors' sentiments over time.

The limit we propose is based on the idea that actors will be affected only through the maximal path conveying the piece of information to the actor. To begin, consider the possible ways in which a piece of information to which actor i' was exposed might be conveyed to actor i over time. The simplest example might be as shown in Figure 3.

In Figure 3 the exogenous effect, or piece of information, $e_{i't}$, has an effect on y_{it+1} on the upper route as mediated by $\alpha k_{i't \rightarrow t+1}$ and γy_{it+1} ($i' \rightarrow i \rightarrow i$). It also has an effect on the lower route as mediated by $\gamma y_{i't+1}$ and $\alpha k_{i't+1 \rightarrow t+2}$ ($i' \rightarrow i' \rightarrow i$). In a sense the two effects are redundant (from an informational perspective), with the only difference consisting of the juncture at which the effect is passed from i' to i , either during the period from t to $t + 1$, in which case the upper route is followed, or during the period from $t + 1$ to $t + 2$, in which case the lower route is followed. Examples of effects that are redundant include the repetition effect shown above: i' conveys information to i and then i' reconveys the information to i ; an echo effect: i' conveys information to i that i then echoes back to i' ; and a parallel effect: i' conveys information to j and k that j and k then independently convey to i . Most importantly, as the number of time points increases, the number of possibly reinforcing paths increases exponentially, potentially causing the explosion in the sentiment.

To isolate the causes of the explosions we differentiate between exposure through a single maximal path from exposure through multiple paths. We begin by creating a

term representing all paths from i' to i over v time periods, $q_{ii't-v \rightarrow t}$:

$$q_{ii't-1 \rightarrow t} = \lambda_{i'} k_{ii't-1 \rightarrow t}$$

$$q_{ii't-2 \rightarrow t} = \sum_{a=1}^N \lambda_{i'} k_{iat-1 \rightarrow t} \lambda_{i'} k_{ait-2 \rightarrow t-1}$$

$$q_{ii't-3 \rightarrow t} = \sum_{a=1}^N \sum_{b=1}^N \lambda_{i'} k_{iat-1 \rightarrow t} \lambda_{i'} k_{abt-2 \rightarrow t-1} \lambda_{i'} k_{bit-3 \rightarrow t-2}$$

and, in general,

$$q_{ii't-v \rightarrow t} = \sum_{a=1}^N \sum_{b=1}^N \dots \sum_{u=1}^N \lambda_{i'} k_{iat-1 \rightarrow t} \lambda_{i'} k_{abt-2 \rightarrow t-1} \lambda_{i'} k_{bct-3 \rightarrow t-2} \dots \lambda_{i'} k_{uu'o \rightarrow 1} \quad (6)$$

In the last expression there are $v - 1$ summation symbols (Σ) and u terms representing interaction ($k_{xx't-v \rightarrow t-v+1}$). The nested summations represent the multiple paths through which $e_{i't-v}$ can affect y_{it} .

As an aside, note that since each of the effects of $e_{i't-v}$ on y_{it} must pass through an actor at each time point, each $q_{ii't-v \rightarrow t}$ can be expressed in terms of the product of the interaction between actor i and all others from $t - 1 \rightarrow t$ and the paths leading from $e_{i't-v}$ to all actors at time point $t - 1$. Indeed it is easily verified from Equation (6) that:

$$q_{ii't-v \rightarrow t} = \sum_{a=1}^N \lambda_{i'} k_{iat-1 \rightarrow t} q_{ai't-v \rightarrow t-1} \quad (7)$$

Equation (7) can be used as an updating formula for easy calculation of $q_{ii't-v \rightarrow t}$.

To remove redundant effects from $q_{ii't-v \rightarrow t}$ we will first identify the effect of $e_{i't-v}$ on y_{it} through the maximum, or primary, path, $mp_{ii't-v \rightarrow t}$. Let $\Omega_{a=1}^N$ represent the maximum for $a = 1$ to N ; then $mp_{ii't-v \rightarrow t}$ can be defined as:

$$mp_{ii't-1 \rightarrow t} = \lambda_{i'} k_{ii't-1 \rightarrow t}$$

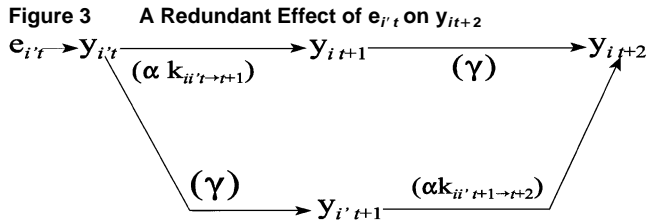
$$mp_{ii't-2 \rightarrow t} = \Omega_{a=1}^N \lambda_{i'} k_{ait-1 \rightarrow t} \lambda_{i'} k_{ait-2 \rightarrow t-1}$$

$$mp_{ii't-3 \rightarrow t} = \Omega_{a=1}^N \Omega_{b=1}^N \lambda_{i'}$$

$$k_{iat-1 \rightarrow t} \lambda_{i'} k_{abt-2 \rightarrow t-1} \lambda_{i'} k_{bit-3 \rightarrow t-2}, \text{ and, in general,}$$

$$mp_{ii't-v \rightarrow t} = \Omega_{a=1}^N \Omega_{b=1}^N \dots \Omega_{u=1}^N \lambda_{i'} k_{iat-1 \rightarrow t} \lambda_{i'} k_{abt-2 \rightarrow t-1} \lambda_{i'} k_{bct-3 \rightarrow t-2} \dots \lambda_{i'} k_{uu'o \rightarrow 1} \quad (8)$$

And the updating formula is:



$$mp_{ii't-v \rightarrow t} = \sum_{a=1}^N \lambda_{i'} k_{ia t-1 \rightarrow t} mp_{ai't-v \rightarrow t-1} \quad (9)$$

The $mp_{ii't-v \rightarrow t}$, by definition, refers to a single path from $e_{i't-v}$ to y_{it} , and therefore contains no “redundant” effects. Thus, for example, if $k_{ii't-1 \rightarrow t}$ is large (or is equal to 1 when $k_{ii't-1 \rightarrow t}$ is dichotomous), then the maximal path connecting an exogenous effect experienced by i' to i is determined the first time i' communicates the fact to i . We can then replace $\sum_{i'} k_{ii't-1 \rightarrow t} y_{i't-1}$ in Model (3) with $\sum_v \sum_{i'} mp_{ii't-v \rightarrow t} e_{i't-v}$ to define a model based only on maximum paths:

$$y_{it} = \sum_{v=1}^t \sum_{i'=1}^N mp_{ii't-v \rightarrow t} e_{i't-v} + e_{it} \quad (10)$$

If people are influenced exclusively by exposure to information, then Model (10) removes the effects of repeated information.⁹ Thus we have extended the theory of persuasion through information to the systemic level by identifying and then eliminating effects of information that circulated throughout the system.

Still, Model (3) had intuitive appeal. In the most basic sense, actors may be influenced by repeated exposure to information (Cacioppo and Petty 1979). In fact, repeated exposure can be stronger when the information is slightly modified (McCullough and Ostrom 1974), which likely occurs through the nonmaximal paths. More generally, embedded in Model (3) was the idea that people are influenced by the sentiments of others around them, beyond the specific information underlying those sentiments. In the social-psychological literature this is described as a normative effect. For example, Asch (1951) demonstrated that people were likely to modify their description of what they observed regarding line length or color in order to conform with confederates who gave intentionally false descriptions. There are extensive explanations regarding why people conform, ranging from the need to retain group membership (Festinger 1950, Schachter 1951), to the need to ensure group cohesion (Cartwright 1968a), to the need to reduce conflict (Steiner 1966), to the reduction of cognitive dissonance (Festinger, 1950). As Sherif (1935) argued, it is the conformity effect that makes the group more than a sum of its parts.

Up to the 1980s there was considerable debate in the social-psychological literature regarding the primacy of information versus normative or conformity effects (e.g., Burnstein and Vinokur 1977, Sanders and Baron 1977). Although early on Deutsch and Gerard (1955) recognized that both processes were possible, this was not fully articulated until each process had been theoretically developed and empirically proven. The two processes have been roughly retained in relatively recently developed “dual process” models. For example, in the elaboration likelihood model (ELM), Petty and Cacioppo (1986) differentiate between central processes (persuasion based on “consideration of the true merits of the information presented in support of an advocacy,” p. 124, emphasis added) and peripheral processes (“the result of some simple cue in the persuasion context that induced change without necessitating scrutiny of the true merits of the information presented,” p. 124, emphasis added). The information/non-information distinction roughly aligns with the distinction between systemic and heuristic processes described by Chaiken (1980, 1987).

We can incorporate normative processes in our model by restoring the effects associated with paths other than the maximum that combined with $mp_{ii't-v \rightarrow t}$ to form $q_{ii't-v \rightarrow t}$. These effects, represented by $q_{ii't-v \rightarrow t} - mp_{ii't-v \rightarrow t}$, are associated with δ in the following model:

$$y_{it} = \sum_{v=1}^t \sum_{i'=1}^N mp_{ii't-v \rightarrow t} e_{i't-v} + \left[\delta \sum_{v=1}^t \sum_{i'=1}^N (q_{ii't-v \rightarrow t} - mp_{ii't-v \rightarrow t}) e_{i't-v} \right] + e_{it} \quad (11)$$

By parameterizing the effects of maximal and non-maximal paths we accommodate social-psychological theories of dual processes in a single model. To set $\delta = 0$ is to indicate that only the maximum path from i' to i will be incorporated into the model, thereby reproducing the information model in Model (10) and essentially reproducing Carley’s (1991) model of adaptation. As δ approaches 1, the normative effect is stronger as actors are distanced from the informational basis of their initial sentiments. To set $\delta = 1$ is to reproduce Model (3), allowing for an explosion of sentiments. At the system level, the internal dynamic of the system overwhelms the information in the system. To specify δ as midrange establishes an anchor for sentiments based on information that has entered the system.¹⁰ Thus the influence model contains balance effects (as actors balance their sentiments to conform to the others around them) and informational effects (as actors’ sentiments are partly defined by the accumulation of information to which they are exposed), and we refer to Model (11) as the B-I model of influence.

The differentiation of maximum paths from all other paths can be used to account for an interesting paradox found in the literature regarding influences on teachers in schools. One camp (Cusick 1983, Lortie 1977) argues that teachers are not strongly influenced by interactions with others, while another camp (Darling-Hammond and McLaughlin 1995, Zeichner and Gore 1989) argues that when one attempts to change the sentiments or behaviors of teachers one must account for, and work through, teachers' influences on one another. Both of these observations may be correct. Teachers who have worked together for a number of years may have considerable influence over one another (high values of α) but have little *new* to say to each other—most of the recent error terms in Model (11) are small, and the effects of older error terms have already been circulated throughout the network. New paths connecting old error terms to current actors are not maximal, and therefore the sentiments of the actors are changing little (Cusick 1983, Lortie 1977). But, if new information entered into the system, in terms of professional development or a new philosophy of teaching, this would result in a large shock to a few actors that would be transmitted, through interactions and the relatively large value of α , to others throughout the network. Thus the teachers are instrumental in transmitting the effects of external shocks to one another (Darling-Hammond and McLaughlin 1995, Zeichner and Gore 1989).

In terms of Model (11), the effect of δ can be represented graphically as in Figure 4, for which $\delta = 0.8$. The actors' sentiments move moderately towards one another in the initial time period, and then approach an asymptote. This process represents a natural occurrence whereby the actors have moderate influence over one another as they

share new information with each other, and then their sentiments subside into their asymptote, neither actor having much influence over the other in the absence of new information with which to persuade the other (Anderson 1971, Burnstein and Vinokur 1977, Hovland and Kelly 1953). By defining an information-based model ($\delta = 0.8$) we have produced a second type of equilibrium, one in which the system moves to an essentially static position, with actors' sentiments eventually ceasing to change.

The Model of Selection: Who Interacts with Whom

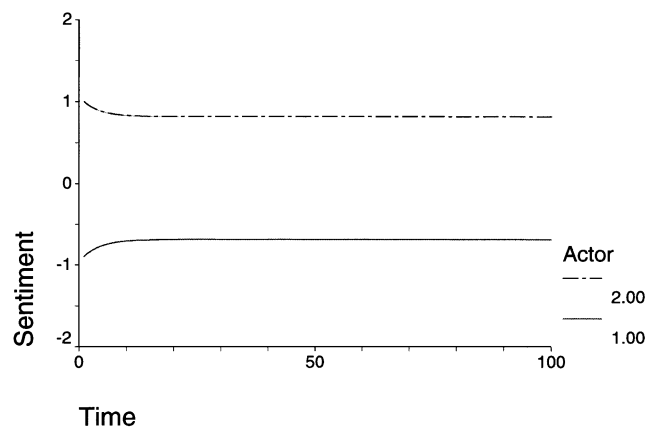
The influence process represented in Model (11) is limited in that the pattern of interaction is considered fixed over time. Therefore in this subsection we develop models of the pattern of interaction between i and i' . The models are described as models of "selection" e.g., (Leenders 1995) suggesting a more proactive role for the actors (Lin and Carley 1995). In the model of selection, actors generate their contexts by seeking out others with whom to interact.

Again we draw on the social-psychological processes of balance and information to build our model. We begin by contrasting the tendency for interaction patterns to persist with the tendency for actors to engage in interactions with others who hold similar sentiments, thus achieving a balance between their attraction/interactions with others and their own sentiments (Blau 1977, Durkheim 1976, Festinger et al. 1950, Heider 1958, Homans 1950, Marsden 1981, Newcomb 1961, Simmel 1955; see Byrne 1971, chapter 2 for a review). For example, teachers who are attempting to be innovative may choose to interact with others who hold beliefs similar to their own (Darling-Hammond and McLaughlin 1995, Lieberman 1995, Zeichner and Gore, 1989). Thus we represent a model for interaction, $k_{ii't-1 \rightarrow t}$, in terms of the extent to which the two actors interacted during the previous interval as well as the commonality in their sentiments:

$$k_{ii't-1 \rightarrow t} = \alpha^{(k)}|y_{it-1} - y_{i't-1}|^* + \gamma^{(k)}k_{ii't-2 \rightarrow t-1}. \quad (12)$$

The parameter $\gamma^{(k)}$ represents the effect of prior interactions between i and i' [the superscript k is used to differentiate the parameters in Model (12) where interaction is the outcome from those in previous models where sentiment was the outcome]. The term $|y_{it-1} - y_{i't-1}|^*$ represents the difference in the sentiments between i and i' , and the model indicates that two actors will be attracted to one another to the extent that their sentiments are similar ($\alpha^{(k)} \leq 0$). The * represents the fact that at each time point, after calculating a matrix of attractiveness values, we subtract off the mean amount of attractiveness that was in the matrix at time point 1. The purpose of this

Figure 4 Trajectories of Sentiments When Effects of Redundant Paths Are Reduced



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pseudo-standardization is to allow for both positive and negative attractiveness values; without it, any distance from an other would reduce future interactions (this effect could also be compensated by including an intercept in the model).

The term $|y_{it-1} - y_{i't-1}|^*$ can be thought of as a representation of the extent to which the sentiments of i and i' overlap. If we consider each actor to have a distribution of sentiment, in a Bayesian sense, then the proportion of overlap in the two distributions is represented by the shaded region in Figure 5 (see Frank and Fahrbach 1997). The metric for $|y_{it-1} - y_{i't-1}|^*$ is in terms of deviates of half a standard deviation in the initial sentiments, providing a natural and substantive interpretation for the specification of the balance effect in Model (12).

Before we proceed we also wish to identify a natural metric for $k_{ii't-1 \rightarrow t}$. Because $k_{ii't-1 \rightarrow t}$ represents extent of interaction over an interval, we specify that $0 \leq k_{ii't-1 \rightarrow t}$. Furthermore, we consider $k_{ii't-1 \rightarrow t}$ to represent the proportion of time during the interval $t-1$ to t that i and i' interact, therefore $0 \leq k_{ii't-1 \rightarrow t} \leq 1$. Note that we do not impose these restrictions to govern systemic processes and a similar range would apply if we were to assign $k_{ii't-1 \rightarrow t}$ to be dichotomous, (e.g., Carley 1990, Stokman and Zeggelink 1996, Wasserman and Pattison 1996). Our scale for k can easily be transformed back to the real line by taking the logit (Agresti, 1984). The selection model becomes:

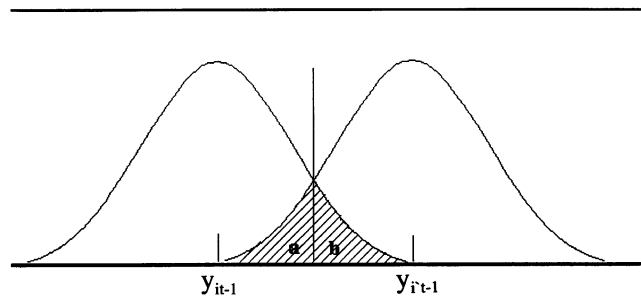
$$\log \left(\frac{[k_{ii't-1 \rightarrow t} = 1]}{1 - [k_{ii't-1 \rightarrow t} = 1]} \right) = \alpha^{(k)} |y_{it-1} - y_{i't-1}|^* + \gamma^{(k)} \log \left(\frac{[k_{ii't-2 \rightarrow t-1} = 1]}{1 - [k_{ii't-1 \rightarrow t} = 1]} \right). \quad (13)$$

Setting $z_{ii't-1 \rightarrow t} = \log([k_{ii't-1 \rightarrow t}]/(1 - [k_{ii't-1 \rightarrow t}]))$, we have:

$$z_{ii't-1 \rightarrow t} = \alpha^{(k)} |y_{it-1} - y_{i't-1}|^* + \gamma^{(k)} z_{ii't-2 \rightarrow t-1}. \quad (14)$$

And the corresponding model for influence is:

Figure 5 Overlap in Distributions of y_{it-1} and $y_{i't-1}$



$$y_{it} = \alpha^{(y)} \sum_{\substack{i'=1 \\ i' \neq i}}^{N-1} \left(\frac{e^{z_{ii't-1 \rightarrow t}}}{1 + e^{z_{ii't-1 \rightarrow t}}} y_{i't-1} \right) + \gamma^{(y)} y_{it-1}. \quad (15)$$

Note that we now write $\alpha^{(y)}$ and $\gamma^{(y)}$ to distinguish from $\alpha^{(k)}$ and $\gamma^{(k)}$ in (14).

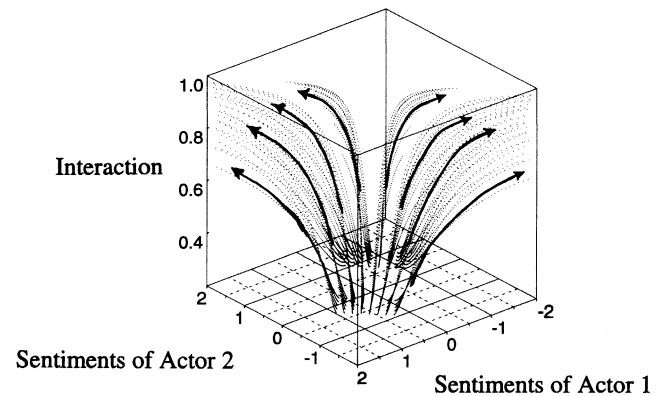
We can now elaborate the two actor system in Model (4) to be defined by three simultaneous equations:

$$\begin{aligned} y_{1t} &= \alpha^{(y)} \frac{e^{z_{11t-1 \rightarrow t}}}{1 + e^{z_{11t-1 \rightarrow t}}} y_{2t-1} + \gamma^{(y)} y_{1t-1}, \\ y_{2t} &= \alpha^{(y)} \frac{e^{z_{22t-1 \rightarrow t}}}{1 + e^{z_{22t-1 \rightarrow t}}} y_{1t-1} + \gamma^{(y)} y_{2t-1}, \\ \text{and } z_{21t-1 \rightarrow t} &= z_{12t-1 \rightarrow t} = z_{t-1 \rightarrow t} \\ &= \alpha^{(k)} |y_{1t-1} - y_{2t-1}|^* + \gamma^{(k)} z_{t-2 \rightarrow t-1}. \end{aligned} \quad (16)$$

Because $z_{t-1 \rightarrow t}$ is no longer considered fixed, the mapping of the system defined in (16) is nonlinear; each of the first two equations incorporates a product of two endogenous variables. But we can infer the systemic processes generated by the equations in (16) by observing that the system has no negative feedback. Therefore $z_{t-1 \rightarrow t}$ can only increase and the system achieves a stable state when $z \rightarrow \infty$, and $k \rightarrow 1$ in which case the system reduces to the system defined by Model (4), with $y_1 \rightarrow \infty$ and $y_2 \rightarrow \infty$ or $y_1 \rightarrow -\infty$ and $y_2 \rightarrow -\infty$.

We are able to graphically demonstrate this process using a phase plot [see the technical appendix for details of how we constructed the phase plot based on the Jacobian of (16)]. In Figure 6, we specified $\alpha^{(y)} = 0.05$, $\alpha^{(k)} = -0.05$, $\delta = 1$, and at $t = 0$, $k = 0.25$. If the mean of the initial sentiments is greater than zero then the sentiment of the actor that is initially negative is pulled towards the positive and the two sentiments explode towards $+\infty$. Simultaneously, their rate of interaction increases and approaches the constant rate of one.

Figure 6 Convergence of System to the Plane $y_1 = y_2$



A parallel process occurs if the initial mean sentiment is negative.

In general, for $N > 2$, fixed points, such as $y_1 = y_2$ in Figure 6, that are associated with negative eigenvalues in the Jacobian of the equations in (16) will be asymptotically stable, attracting other points in their neighborhoods. Fixed points that are associated with positive eigenvalues in the Jacobian will be asymptotically unstable, repelling other points in their neighborhood (Alligood et al. 1996). In other words, because the extent of interaction becomes a constant, the behavior of the system defined by Model (16) is not appreciably more complex than the behavior of the system defined by Model (4).

Not only is the behavior of the system defined by Model (16) not appreciably more complex than that defined by Model (4), Model (16) is theoretically incomplete because it does not account for information effects. In particular, though actors may prefer to interact with others like themselves to maintain a cognitive balance, they may also seek to interact with others who have access to, and therefore have been influenced by, competing information. They may seek new information because it helps them to achieve their ends (Alchain and Demsetz, 1972, Burt 1992, Katz and Kahn 1978), reduce uncertainty (Radner 1986), make them more powerful (Burns and Stalker 1961, Pettigrew 1972), give them a better understanding of their position on an issue (Rosen 1961), or out of sheer curiosity (Freedman 1965). In an interesting social-psychological theory, McGuire and Papageorgis (1962) argue that actors use small amounts of new information to "inoculate" themselves against positions counter to their own. Newcomers to an organization are especially likely to proactively seek information (Miller and Jablin 1991, Morrison 1993, Reichers 1987).

Note that actors typically are not aware of the information that other actors have (Macdonald 1995). Therefore we do not model actors as pursuing pieces of information to which they know others have been exposed. Instead they pursue the *potential* information that might be gained through an interaction. Specifically, potential information gained by actor i as a result of interacting with i' is defined by the change in maximum paths connecting i to all exogenous effects that occur as a result of i interacting with i' . Define $mp_{ji}^*_{t-v \rightarrow t}$ to represent the maximum path between an exogenous effect that actor j experienced at time $t - v$ and actor i , assuming that actor i interacts with actor i' from $t - 1$ to t (at a prespecified rate). Thus the differences between $mp_{ji}^*_{t-v \rightarrow t}$ and $mp_{ji}^*_{t-v \rightarrow t-1}$ represent the changes in exposure to new information that result when i engages in interaction with i' . The effect of potential information is then associated with ζ in the following model:

$$k_{i'i' t-1 \rightarrow t} = \alpha^{(k)} |y_{it-1} - y_{i't-1}|^* + \gamma^{(k)} k_{i'i' t-2 \rightarrow t-1} + \zeta \sum_{\substack{j=1 \\ j \neq i}}^{N-1} \sum_{v=1}^{t-2} (mp_{ji}^*_{t-v \rightarrow t} - mp_{ji}^*_{t-v \rightarrow t-1}). \quad (17)$$

We assume that ζ is positive; therefore actors tend to interact with others who can increase their exposure to information (note that ζ may have to take relatively large values—in the 100s—as the $mp_{ji}^*_{t-v \rightarrow t}$ and $mp_{ji}^*_{t-v \rightarrow t-1}$ are considerably less than 1 as is the difference between them). It is this effect associated with the pursuit of information that provides an important counterbalance to the homophily effect, preventing the interaction between a pair of actors to steadily increase over time.^{11,12} Thus the B-I selection model in Model (17) contains balance effects (as actors seek to interact with others who hold similar sentiments) and informational effects (as actors seek to interact with others who have access to new information).

We use the counterbalancing forces of information and balance to generate the third and final form of equilibrium in complex systems, an equilibrium that is bounded but chaotic. Methodologically, the inclusion of terms such as $mp_{ji}^*_{t-v \rightarrow t}$ and $mp_{ji}^*_{t-v \rightarrow t-1}$ makes it difficult to explore the properties of the system through differential equations. Terms based on maximal paths draw on information contained in the history of the system, and so the system cannot be represented through a Markovian framework, defined primarily in terms of the immediate state and rate of change of the system at any fixed point. Therefore we turn to simulations to explore the systemic processes implied by models containing terms based on maximal paths.

There are two sets of conditions that we can define in the simulations: starting values and parameter values. For the starting values, we must decide the size of the system (the number of actors), the initial pattern of interaction, and the initial distribution of sentiments. Of course, given the permutations of just these conditions there are a myriad of simulations that could be conducted. In general, we choose our starting values to explore how the structures defining organizational culture might emerge among a group of actors or how they might evolve given existing organizational structures and exogenous shocks to the system. For our parameters, we chose values to generate equilibria other than the exploding or stagnant equilibria we demonstrated for the simpler models.

We will use five actors in the examples we develop. Like Mark (1998), we have chosen a small number of actors because the bases of organizational processes can often be understood in terms of small group dynamics

(Homans 1950, Sayles 1980, Shaw 1981) which are analogous to interactions among larger components such as departments (Smith 1973). We use five so that there is the possibility for subgroups to emerge, as well as for an actor to bridge between subgroups.

While only Carley (1991) has extensively discussed the impact of subgroups on systemic processes, our focus is on subgroups because the internal differentiation of organizations is typically characterized in terms of subgroups (Blau 1977, Durkheim 1933, Homans 1950, Roethlisberger and Dickson 1941, Simmel 1955, Simon 1965). For example, organizations may consist of integrated subgroups because organizations evolve through the linkages of subgroups (Simon 1965), because subgroups are imposed on organizations for managerial efficiency (Granovetter 1973, Simmel 1955), or because subgroups emerge as organizations grow and interactions among actors cannot be sustained at levels high enough to integrate each actor directly into the common organization (Festinger et al. 1950, Newcomb et al. 1965, Robinson 1981). Most relevant for us, subgroups may be areas of strong subcultures in organizations (Sackmann 1992).

Consistent with the idea that the organizational structures are to emerge among a previously unorganized set of actors, we begin by initiating our simulations with some subsets of actors holding similar sentiments (that may have formed based on common background characteristics), but with the pattern of interaction as uniform across all pairs of actors (assuming that no pair of actors had special reasons to interact prior to the convening of the simulation). Specifically, two actors were initiated with negative sentiments (-1.7 , -1.4), and two actors with positive sentiments, (1.4 , 1.7). If one considers the distribution of sentiment in a standardized metric then there is minimal overlap in the distributions (in a Bayesian sense) of the sentiments of the members of the two pairs, and therefore they do not seek to interact with one another to achieve balance between their interactions and their sentiments. The last actor is almost neutral, beginning with sentiment -0.1 .¹³

We designated the initial pattern of interaction to be uniformly 0.25 . Thus, consistent with row normalization, each actor's initial marginal adds to unity (assuming a value of 0 on the diagonal), although the restriction does not apply for $t > 0$. This baseline value of 0.25 was also used in the construction of $mp_{jit}^* - v_{i,t}$, implying that an actor seeks interaction to the extent that information will be obtained by interacting with the other at the 0.25 level. All external disturbances in sentiment and interaction after time zero were specified to be zero so that we could observe the effects of the internal dynamics of the system.

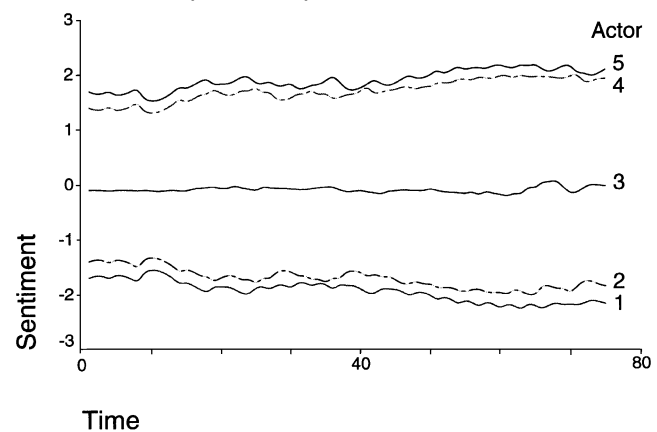
Yet there is still the effect of the system being open to exogenous effects, as actors seek to interact with others to increase their potential for exposure to information.

In the influence Model (11) we specified $\gamma^{(y)} = 1$ indicating that sentiments would remain constant in the absence of influence, $\alpha^{(y)} = 0.1$, allowing a moderate effect of influence, and $\delta = 0.8$, allowing some effects to accumulate through multiple paths (that will accrue primarily within subgroups). In the selection Model (17), we specified $\gamma^{(k)} = 1$, and $\alpha^{(k)} = -0.1$, allowing a moderate homophily effect, and $\zeta = 250$, a moderate effect that provides a counterbalance to actors' desires to interact with others who hold sentiments similar to their own, while not artificially requiring constant interaction between disparate actors. The results are shown in Figure 7.

In Figure 7 we observe the dynamic processes of the third form of equilibrium characteristic of a complex system, in which the system continually changes, but the structure is bounded, periodically returning to one of a few states (this is known as a "strange attractor"—Gleick 1987). In particular, note that actor 3's sentiments, y_{3t} , oscillate between positive and negative values as the actor alternates interacting with members of the two pairs.¹⁴ The members of a pair with whom actor 3 interacts influence actor 3 until actor 3 seeks information by interacting with members of the other pair. Actor 3 is then influenced through interactions with the other pair and a cycle is completed. Actor 3's behavior extends to a cycle the behavior found in the experimental setting by Brickman and D'Amato (1975) in which actors explore sources of new information and then interact with others like themselves.

There are three distinct phases of the system. Two occur when actors 3 is interacting primarily with actors 1

Figure 7 Oscillation Produced by Internal Dynamics of System (No Shocks)



and 2 or with actors 4 and 5, in which cases the sentiments across the system are least consensual, and the third when actor 3 is intermediate between the two pairs, in which case the sentiments are most consensual. The apparently random behavior of the system (which we have determined continues for at least 500 time points) is bounded and has a periodic tendency implying sensitivity to initial conditions, the trademarks of chaotic complex systems (Alligood et al. 1996, Stacey 1996, Stewart 1989, Thietart and Forgues 1995).

Actor 3's vacillation between pairs affects each actor in the system. When actor 3 interacts with members of a pair actor 3 influences them, bringing their sentiments closer to the mean sentiment. In this sense, actor 3 functions as a weak tie (Granovetter 1973), conveying effects originating in the other pair. When not interacting with actor 3, the members of each pair interact with each other without the counterbalancing influence of actor 3, and thus their sentiments become accentuated, moving away from the mean. Therefore each actor's sentiment oscillates and the bridging actor 3 prevents the sentiments of members of either pair from diverging from the mean, thus preserving the integrity of the system (Blau 1977, Burt 1992, Durkheim 1933, Simmel, 1955).

Stochastic Systems: Systemic Responses to External Shocks

Given a baseline understanding of the internal dynamics of the system characterized by Models (11) and (17), we can now explore the effects of nonconstant exogenous shocks to the system. Here it is important to emphasize that by "exogenous" we mean shocks that are exogenous to the system. For example, in a school such shocks may be attributed to changes in legislation, teacher training, communications from a central administration, etc. But the shocks may also be defined as emanating from the actors in a way that is not explained by systemic processes. In the example of the school, the "shock" that a teacher experiences in her orientation towards teaching based on self-reflection is considered exogenous to the system, although clearly it is not exogenous to the school. Therefore we do not rule out the possibility that the members of an organization can be responsible for the transformation of the organization. In fact, this is a central feature of the processes we model.

We begin by considering the effect of forces that bring actors together, assigning an external shock in sentiment of 0.5 to actors 1 and 2 and of -0.5 to actors 4 and 5, or force them apart, assigning an external shock in sentiment of -0.5 to actors 1 and 2 and of 0.5 to actors 4 and 5. The difference between these types of shocks can

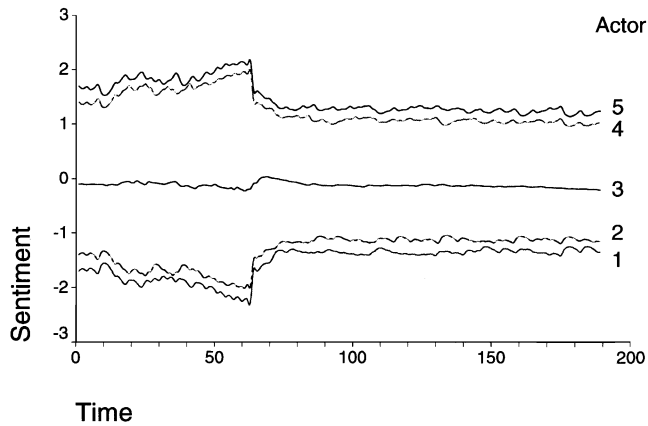
be considered critical to the development of an organization, either increasing cohesiveness (Woodward 1965) or factionalization (Sherif and Sherif 1966). For example, in schools, teachers may be differentially exposed to exogenous effects that exacerbate existing factions (Frank 1996, McLaughlin and Marsh 1979, Powell et al. 1985) or that induce consensus (e.g., Darling-Hammond and McLaughlin 1995, Rosenholtz 1987). We begin by showing the effects of the external shocks administered at the time of least consensus in the system ($t = 64$) in Figures 8a and 8b.

In Figures 8a and 8b we observe that the effects of the exogenous shocks did not dramatically alter the nature of the equilibrium of the system, regardless of whether the shocks were towards consensus building or to increase factionalization. In either case we observe oscillation similar to what we observed in Figure 7. This is not to say that the system was unaffected by the external disturbances. Clearly the actors are closer to consensus after the consensus shock in Figure 8a and are further from consensus after the factionalization shock in Figure 8b. But the point is that the oscillating pattern reemerges, suggesting that the equilibrium is resistant to some exogenous effects.

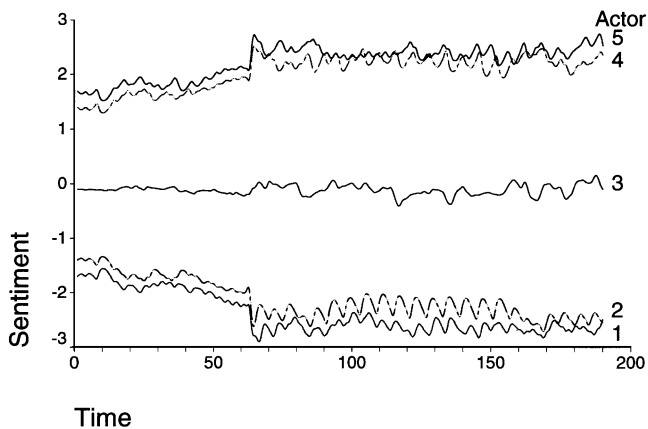
But the effects of exogenous shocks to dynamic systems depend on the time at which they are administered (Stacey 1996, Thietart & Forgues, 1995). In Figure 8c we observe that the oscillating equilibrium does not reemerge when exogenous shocks increasing consensus are applied to the system when it is most consensual ($t = 81$). Instead, the effect of increasing consensus is to bring actor 3 close enough to actors 1 and 2 in sentiment such that the effects of influence [as in Model (11)] and balance [as in Model (17)] overwhelm the pursuit of potential information [the counterbalance in Model (17)]. Actor 3 is assimilated by actors 1 and 2 and ceases bridging between the two pairs (actors 3's movement towards negative sentiment continued when the simulation was run for $t = 500$). This demonstrates an important potential paradox for those who seek to modify organizations. In this case a force that directly induces consensus actually indirectly increases factionalization by eliminating the role of the bridging actor. Such a process is not inconsistent with organizational evolution in response to external crises described for example by Durkheim (1933) and Woodward (1965) and is consistent with those described by McLaughlin and Marsh (1979) upon the introduction of professional development in a school.

We now explore the effects of introducing exogenous effects to individual actors independently. By doing so we develop a longitudinal conceptualization of centrality. Typically, centrality in a social network is defined in

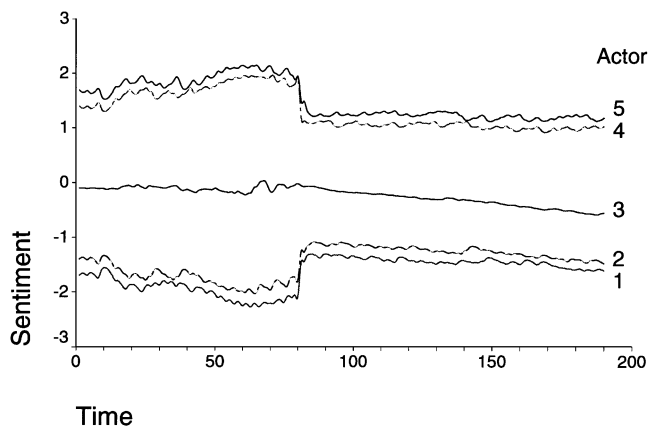
Figure 8 Trajectories of Sentiment
8a. Consensus-Inducing Shock at Time 64



8b. Faction-Inducing Shock at Time 64



8c. Consensus-Inducing Shock at Time 81



terms of a static state of interactions (c.f., Freeman, 1978/1979, Friedkin, 1991). Here we consider the effect that one actor's change in sentiment will have on the distribution of sentiment and the pattern of interaction, which

together define the dynamic system. In particular, we separately consider the effect of shocks of positive one to each actor's sentiment at $t = 64$ as shown in Figures 9a through 9e.

Clearly, when the exogenous effect is experienced by actor 3 it has the greatest effect on the system. Note that 9c is plotted on a larger scale than the other figures. The positive shock that actor 3 experiences moves actor 3 close enough in sentiment to actors 4 and 5 for the effects of balance and then influence to overwhelm the effect of information seeking. The result is that actor 3 joins actors 4 and 5, and the three actors move together towards positive sentiments. Furthermore, this positive trend eventually subsumes actors 1 and 2, as all actors exhibit positive sentiments by $t = 140$.

Figures 9a through 9e reveal how the effects of exogenous shocks to a system are mediated by specific actors. In this case, a shock administered to a bridging actor reverberates throughout the system, having a strong impact on the pattern of interaction as well as the distribution of sentiment, while shocks administered to actors affiliated with the others have moderate effects on the mean sentiment, but do not substantially alter the form of equilibrium in the system. While there are subtle differences among the effects of shocks administered to other actors (shocks to the more negative actors 1 and 2 have more of an initial effect but less of an enduring effect than shocks to actors 4 and 5), the extreme effect of the shock to actor 3 suggests that actors occupying the boundary spanner role serve as focal points for those seeking to change the average sentiment in an organization. In the language of Abrahamson and Rosenkopf (1997), actor (3) is a boundary pressure point.

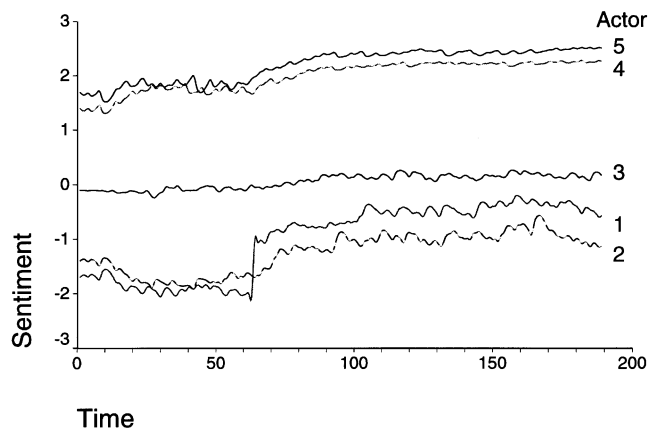
From the methodological perspective, it is critical to note that actor 3's role cannot be defined completely in terms of the matrix of interactions at $t = 64$:

$$K_{64} = \begin{bmatrix} 0 & 0.999 & 0.293 & 0.056 & 0.288 \\ 0.999 & 0 & 0.165 & 0.109 & 0.110 \\ 0.293 & 0.165 & 0 & 0.311 & 0.358 \\ 0.056 & 0.109 & 0.311 & 0 & 0.999 \\ 0.288 & 0.110 & 0.358 & 0.999 & 0 \end{bmatrix},$$

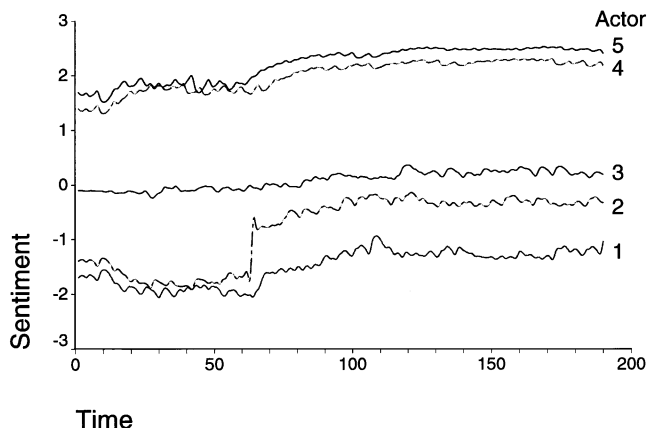
where actor 3 does not have the highest centrality measure in terms of degree (as defined by the row marginals) and is moderate in terms of eigenvalue-based centrality (Bonacich 1972) or information-based centrality (Stephenson and Zelen 1989). We have thus extended the conceptualization of centrality in a longitudinal sense, accounting for the effect of a shock to an actor on the evolution of structure of interaction and the distribution of sentiment in the system.

Figure 9 Trajectories of Sentiment with Shocks at Time 64

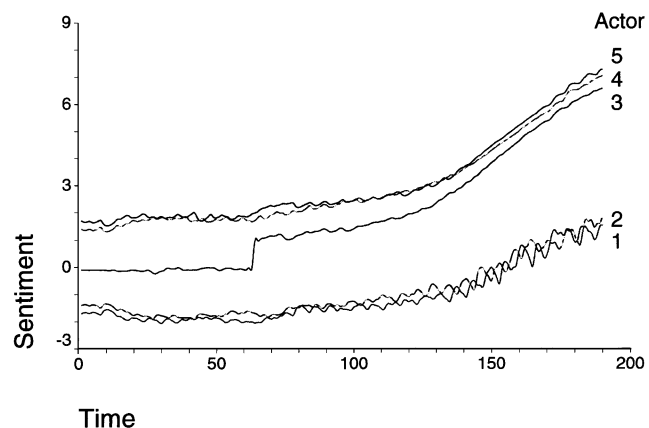
9a. Shock to Actor 1



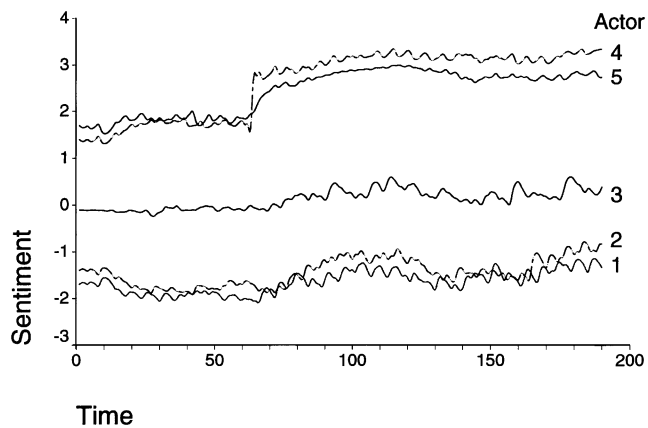
9b. Shock to Actor 2



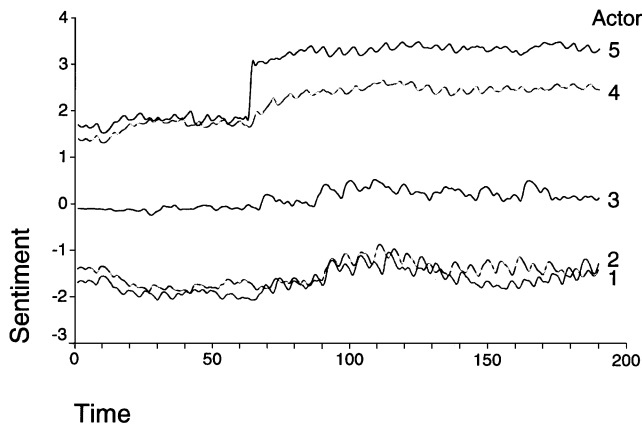
9c. Shock to Actor 3



9d. Shock to Actor 4



9e. Shock to Actor 5



Organizations as Complex Systems

We have defined a complex system by incorporating the social-psychological principles of balance and informa-

tion (B-I) into models of influence and selection and exploring the systemic implications of each process over time. We identified information-based influence as a

potential anchor for actors' sentiments so that they are not overwhelmed by normative influence. In the model of selection, we identified the pursuit of information as an important counterbalance to the effect of homophily (interacting with others like oneself).

By defining our models at the level of the individual or dyad we represent the dual agency of actors who react to contexts in organizational culture that they help to construct (e.g., Lin and Carley 1995). In the influence model, actors essentially react to the information in the organizational culture to which they are exposed. In the selection model, actors proactively seek partners for interacting, thus establishing the contexts that affect the information and conformity pressures to which they are exposed.

Because we have focused on changes in sentiment that underlie culture, we have responded to Radner's (1992) call to go beyond economic models of organizations defined primarily in terms of the effects of information and productivity. Such models typically assume that actors are atomistic, or at most share preferences (e.g., the "teams" described by Marschak and Radner 1972), but do not address the systemic processes through which, for example, consensus in sentiment emerges. Moreover, economic models that are based on methodological individualism still do not account for systemic processes such as the circulation of information that we account for in our models. We also have extended social-psychological models by representing their systemic implications, for example, by representing the effects of circulating information.

By specifying formal mathematical models we have gone beyond the use of "social networks" and "chaos theory" as metaphors. Though organizations may be complex because of the range of exogenous effects to which they are exposed, we have used the tools of dynamic systems to establish that the evolution of the culture of an organization is itself a complex chaotic process. Furthermore, organizations may be complex because of variation in the characteristics of its members, but our system is governed by only a small number of homogeneous parameters ($\gamma^{(y)}$, $\alpha^{(y)}$, δ , $\gamma^{(k)}$, $\alpha^{(k)}$, and ζ) applying to all actors in the system. Thus one answer to the question "What makes organizations complex systems?" can be found in the processes of influence and selection that underlie organizational culture.

By exploring the processes through which organizational culture emerges we generate an alternative to our original question. Now we ask: "What makes complex systems become organizations?" To be sure, organizations are defined as "an arrangement of interdependent

parts, each having a special function with respect to the whole" (Cartwright 1968b p. 1). But this is definitional, and does not address the emergence of an organization nor its culture. By exploring the self-organization of the system (Coleman 1990, Hayek, 1973) we can now ask whether the organizational culture may come first, as individuals gather, influence each other, share and pursue information through interaction, etc. If so, then at what point is the organization defined? When it takes on formal rules or structures? Perhaps the definition is merely in the density of interaction. Or, perhaps it is in the values of the parameters. For example, O'Reilly and Chatman (1996) suggest that when $\alpha^{(y)}$ and $\alpha^{(k)}$ become large the system is transformed. Certainly δ defines an essential aspect of the culture of the organization.

Our models do more than just characterize the internal processes of organizations. Taking the actors as individuals, the models demonstrate how exogenous effects enter and reverberate throughout an organization, allowing us to specify the elusive mechanisms through which institutions penetrate organizational boundaries (DiMaggio and Powell 1991). For example, in a school we might model how teachers come to endorse the tracking of students, having been exposed to various divisions of labor and segmentation in other organizations outside the school. In this case, each teacher need not be equally exposed to the exogenous effect, as the effect is transmitted through interactions among teachers.

At the level of the school, the internal structures of the school affect how the school responds to exogenous shocks. As a corollary at the level of the teacher, each teacher affects how the organization responds to any exogenous shock as each teacher helps to construct the structures of sentiment and pattern of interaction through which the shock is transmitted. For example, Figures 9a through 9e showed how the pattern of interaction that actors construct affects how they respond to external shocks, revealing that the system was most sensitive to shocks experienced by the bridging actor **3**. But although the system is most responsive to shocks experienced by actor **3**, we do not characterize the system as being controlled by one actor responding to an external contingency. Instead we observe the less rational systemic response through the culture jointly constructed by the participating actors.

As the structures of the organization change in response to exogenous shocks the organization "learns" from its environment (Macdonald 1995). Exogenous shocks cause learning at two levels. First, individuals learn as they are exposed to new information. In turn, this changes their sentiments and interactions. Second,

changes in the overall *distribution* of sentiment and *pattern* of interaction constitute learning at the organizational level (Hedberg 1981). Conversely, the organizational structures at any given time affect how the organization absorbs information. Thus organizational learning is a function of the interaction of exogenous shocks and the existing organizational structures that are partly functions of previous shocks (Stymne 1970).

The processes we observe in our systems may be generalized beyond our small groups of two or five. In mathematical terms, whenever the pattern of interaction becomes static we may expect the equilibrium distribution of sentiment to conform to the eigenvalues of a matrix representing the interaction. In theoretical terms what we have learned about the processes through which subsets of actors become integrated through bridging actors should apply to subgroups in larger systems. Smith (1973) has extended this argument, suggesting that the processes we observe among actors in a small group are analogous to the processes we observe among larger units of an organization. Through this analogy, studies of small groups in the laboratory, and simulation and mathematical methods applied to dynamic systems, may be the most informative in the study of organizations.

Of course, our models have several limitations. To begin, from the social-psychological perspective we could explore the extent to which persuasion is influenced by factors affecting the extent of communication during interaction, such as through distraction, the motivation of the receiver, the prior knowledge of the receiver for generating schema for integrating a message, or characteristics of the messenger (see Petty and Cacioppo 1996).

We have assumed that actors are generally aware of each other's sentiments or exposure to information based on observation in common settings and through patterns of association (e.g., Newcomb 1950). One could extend Model (17) by explicitly including the processes through which actors become aware of each other's sentiments and informational exposure through previous interaction, or through information exchanged through common others. These processes could be represented by including terms such as the product of similarity of sentiments and prior interaction ($|y_{i,t-1} - y_{i',t-1}| * k_{ii',t-1 \rightarrow t}$) or of similarity in sentiments and the extent to which there are intermediaries who can inform actors of each other's sentiments ($|y_{i,t-1} - y_{i',t-1}| * \sum_j k_{ij,t-1 \rightarrow t} k_{j'i',t-1 \rightarrow t}$). We could also incorporate the feature that two actors are more likely to interact if they interact with many common others, thus achieving balance in their pattern of interaction (Davis 1967, Heider 1958, Newcomb 1961; see Frank and Fahrbach 1997 for one possible model).

We have also assumed that information is completely

and perfectly communicated. Alternatively we could explore the implications of information that is partially communicated, either intentionally or not. Such an assumption is often addressed in economic models (e.g., Radner 1986) or policy oriented models (Stokman and Zeggelink 1996). One implication is that information may be partly lost in a system as it is inefficiently communicated. To some extent we account for these effects through small values of α , which is exponentiated through chains of interaction. More generally, this opens up an exciting possibility to explore the effects of lost information beyond the imprint it leaves on organizational structures.

We could explore the implications of our models for alternative initial structures, such as a core-periphery structure of interaction (e.g., Abrahamson and Rosenkopf 1997). What are the implications of our models for the efficiencies of information diffusion through various patterns of interaction? By allowing for the structure itself to be modified through exogenous effects we can explore the rate at which the structure becomes modified and how this interacts with the efficiency of information diffusion. We could also then explore the effects of variation in shocks (e.g., intermittent, oscillating—see Hannan and Freeman 1984) as well as the interaction with variation in internal culture (e.g., Lin and Carley 1995).

We can also extend our models by introducing exogenous effects that are constant across time or people. For example, in theories of mixed influence of mass media and diffusion, the mass media effects can be introduced as near constant shocks in sentiment across the system to all actors at one time point. Similarly, there could be a wave of shocks to the pattern of interaction at a single time point that could be introduced. Such would be the case for teachers who interact frequently during a professional development program at their school. We can also explore effects of shocks to actors that are constant across time. For example, a teacher may be continually exposed to a particular emphasis on a particular philosophy in his or her home that affects the teacher's orientation to teaching.

We have narrowly explored the bases of organizational culture in terms of the distribution of a single sentiment and the pattern of interaction regarding that sentiment. Of course, organizational culture is more general than that which can be represented in the distribution of a single sentiment, and may even include more metasentiments such as morale or attitude towards the organization. On the other hand, these more general cultures are built on the processes underlying specific sentiments. For example, the processes through which teachers develop attitudes towards tracking students, team teaching, using

textbooks, teaching students with disabilities, etc. culminate in a general organizational culture. In turn, this culture may affect teacher's level of commitment and morale (e.g., Rosenholtz 1989). Therefore our analyses may provide insight into the processes through which more ethereal aspects of organizational culture are generated.

Of course, we must eventually move beyond simulated data and theoretical models. We add to the call for more longitudinal data including sentiments and interactions among actors (Leenders 1995), and we encourage the efforts of those who have pursued estimating the parameters in simultaneous equations defining complex systems (Carley 1996, Frank 1995, Leenders 1995, Snijders, 1996).

While each of the extensions described above could prove valuable, we wish to emphasize here that the most basic and general processes of selection and influence alone can generate complex behaviors in organizations. What is required is an anchoring mechanism, such as the core of information we use in our models, and both positive and negative feedback, such as the offsetting effects of balance and information-seeking in our model of selection. Most generally, we hope that our work here will help others specify models that are consistent with the social-psychological theories of influence and selection that underlie organizational cultures. It is reasonable to expect that these models, without extensions, should have the potential to characterize many of the complex processes observed in organizations.

Acknowledgments

Portions of this paper were presented at the annual meeting of the Sunbelt Social Networks Conference, San Diego, California, February, 1997. The authors thank Noah Friedkin, JiQiang Xu, and David Krackhardt for their thoughtful comments on this work.

Appendix

To explore the dynamic characteristics of Model (4), we rewrite it as a set of linear differential equations. This is done by subtracting γy_{1t-1} from both sides, and setting $\gamma = 1$. This gives us

$$\begin{aligned} \Delta y_1 &= \alpha k y_{2 \ t-1}, \\ \Delta y_2 &= \alpha k y_{1 \ t-1}. \end{aligned} \tag{18}$$

Because the equations in (18) are expressed for change over one unit in time, we can rewrite it as

$$\begin{aligned} \frac{\Delta y_1}{1} &= \frac{\Delta y_1}{\Delta t} = \alpha k y_{2 \ t-1} = \alpha k y_{2 \ t-\Delta t}, \\ \frac{\Delta y_2}{1} &= \frac{\Delta y_2}{\Delta t} = \alpha k y_{1 \ t-1} = \alpha k y_{1 \ t-\Delta t}, \end{aligned} \tag{19}$$

where the right hand sides are obtained by replacing $t - 1$ with $t - \Delta t$ (which is sensible since the original units were arbitrary).

By allowing the time interval to become infinitely small in the limit

we can use the equations in (19) as a basis for exploring the dynamic properties of the system [see Doreian and Hummon, 1976, p. 127, for an example of taking the limit in Model (19)]. In particular, the equations in (19) can be used as a basis for a mapping of the system:

$$\begin{bmatrix} \frac{\partial y_1}{\partial t} \\ \frac{\partial y_2}{\partial t} \end{bmatrix} = A \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 & \alpha k \\ \alpha k & 0 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}. \tag{20}$$

Defining the system in this way, the eigenvalues and vectors of **A** indicate the dynamic behavior of the system (Alligood et al 1996, pp. 286–287). The eigenvalues of **A** are $(\alpha k, -\alpha k)$, with corresponding eigenvectors $\mathbf{u}_1 = (1,1)$ and $\mathbf{u}_2 = (1, -1)$ that define the lines $(y_1 = y_2)$ and $(y_1 = -y_2)$ respectively.

The general solution of Model (20) is given by:

$$\begin{bmatrix} y_{1t} \\ y_{2t} \end{bmatrix} = c_1 e^{\alpha k t} \mathbf{u}_1 + c_2 e^{-\alpha k t} \mathbf{u}_2. \tag{21}$$

While the constants c_1 and c_2 must be defined relative to a fixed set of starting points, it is clear that for any constants c_1, c_2 , as t becomes large the \mathbf{u}_2 term becomes negligible so that the system asymptotically approaches the line $(y_1 = y_2)$ defined by \mathbf{u}_1 . Together the two eigenvectors, \mathbf{u}_1 and \mathbf{u}_2 , span the entire phase space of the system as shown in Figure 1 (with $\alpha = 0.1$). All initial values on the line $y_1 = -y_2$ approach the origin as t increases. For all other initial values, $y_1 \rightarrow \infty$ and $y_2 \rightarrow \infty$, or $y_1 \rightarrow -\infty$ and $y_2 \rightarrow -\infty$ which is represented by the asymptote $y_1 = y_2$ in Figure 1 (see (Alligood et al. 1996, p. 287).¹⁵ The fixed point at the origin is a saddle point, representing a tenuous balance between movement along the two eigenvectors (Alligood et al. 1996, pp. 63–65). This basic characterization will apply in systems for $N > 2$; the lines defined by eigenvectors associated with positive eigenvalues will be asymptotically stable, that is, they will be both stable and attract the trajectories of nearby initial conditions. Eigenvectors associated with negative eigenvalues will be unstable sources, repelling the trajectories of nearby starting conditions.

To represent the system defined by Model (15) in which the extent of interaction may also change as a function of actors' sentiments, we again use differential equations, following a procedure similar to that in constructing the mapping in (20). Here we set $\gamma^{(y)} = \gamma^{(k)} = 1$ and subtract the corresponding components from each side, and set all external shocks equal to zero to yield:

$$\begin{aligned} \Delta y_1 &= \alpha^{(y)} \frac{e^z}{1 + e^z} y_{2 \ t-1}, \Delta y_2 = \alpha^{(y)} \frac{e^z}{1 + e^z} y_{1 \ t-1}, \\ \Delta z &= \alpha^{(k)} |y_{1 \ t-1} - y_{2 \ t-1}|. \end{aligned} \tag{22}$$

From the equations in (22) we can define a system of differential equations as we did in constructing the mapping in (20). In general, the identification of a fixed point of a system as a sink or a source depends on the linear behavior of the system near that fixed point. In the unidimensional case this linear component is captured by the first derivative of the function defining the system. In the multidimensional case the linear behavior of the system is captured by the matrix of partial first derivatives, the Jacobian, and the mapping of the system defined by the equations in (22) can be explored through the eigenvalues of the Jacobian. The Jacobian for the equations in (22) is (assuming $y_1 > y_2$):

$$\begin{bmatrix} 0 & \alpha^{(y)} \frac{e^z}{1 + e^z} & y_2 \alpha^{(y)} \frac{e^z}{(1 + e^z)^2} \\ \alpha^{(y)} \frac{e^z}{1 + e^z} & 0 & y_1 \alpha^{(y)} \frac{e^z}{(1 + e^z)^2} \\ y_1 \alpha^{(k)} & -y_2 \alpha^{(k)} & 0 \end{bmatrix}. \quad (23)$$

Evaluated as $z \rightarrow \infty$, that is, when the two actors interact almost 100% of the time, each eigenvalue of the Jacobian is negative, indicating that the fixed point is asymptotically stable (it is both stable and attracts other points in the neighborhood). The eigenvectors correspond to those for the two-dimensional system in which the pattern of interaction was considered constant.

Endnotes

¹Sentiments also might refer to actors’ understandings of the organizational mission, orientations to conducting the business of the organization, morale, etc.

²By specifying formal models, we establish a common basis for critiquing and extending the models (Pélli 1997).

³Even if organizations do not modify their cultures rapidly enough to adapt to external contingencies (Hannan and Freeman 1984), the cultures of the organizations that do survive are continuously modified through exposure to exogenous effects.

⁴The term cointegration is borrowed from time series analysis in which two nonstationary processes with stationary residual sequences are integrated of the same order and become intertwined over time through mutual feedback (see Enders 1995, p. 69).

⁵Note that model has no intercept as the mean value of y in the system is not relevant to systemic processes (Mead 1967). This may be especially true for attitudinal scales which have a somewhat arbitrary zero point.

⁶In general, we present discrete time models, as most organizations exhibit a natural periodicity as defined by Alligood et al. (1996). For example, in schools the periods are defined by the school day, in which we assume that effects of external disturbances can enter only between school days and that the system is deterministic over the course of the school day. Therefore it is sensible to observe the system at the end of each day. Similar processes are likely to apply in other organizations, with the intervals defined by the exposure of the actors to external disturbances, either at the end of the working day or week. In contrast, purely deterministic systems such as specified by DeVree and Dagavos (1994) do not clearly specify the point at which errors, or external disturbances, may enter the system. In the Markov literature the phenomenon of the error entering only at discrete periods is referred to as impulse control (Van der Shouten 1983) and can be accommodated by discrete time models.

⁷The system is also often constrained by use of row normalization (Friedkin and Johnsen 1990, French 1956, Friedkin and Cook 1990, Harary 1959). Row normalization is defined by $\sum_{i'} k_{ii' t-1 \rightarrow t} = 1$, thereby preventing explosions in sentiment. French (1956) and Lewin (1951) have been cited for a theoretical basis for row normalization. Yet, the basis in French for row normalization is given as: “It will be noted that each row of [K] sums to 1 because it represents the total opinion of a member, and the fractions along the row represent the proportion of that opinion determined by each person” (p. 192). While this statement clearly endorses row normalization, it does not provide a theoretical

basis for the procedure. Nor could we find a theoretical basis in Lewin for row normalization. Although Lewin repeatedly discusses the forces on, and interdependencies among, parts of the whole person which could be taken as moderate support for row normalization, these references do not imply a restriction on the forces to which an individual is exposed. Moreover, Lewin’s use of force theory borrowed from the physical sciences would suggest that, while the vector representing the direction of the force might be restricted in length for convenience, the magnitude of the force is not constrained.

At the level of the system, most of the time that row normalization is used the model “leads to an equilibrium wherein everyone eventually agrees on the characteristics of the job [the sentiment used in the example]. The fact that everyone does not agree on such job evaluations is what prompted researchers to explore the SIP [social information processing—influence] model in the first place. *Therefore for the SIP model to make such a long-run equilibrium prediction is problematic*” (Krackhardt and Brass 1994, p. 219, italics added). The use of row normalization therefore limits the behavior of the system.

Another complication arises when **K** is allowed to vary over time. If **K** is changing, at what time should row normalization take place? If one row normalizes solely at one time point, there is no guarantee that the elements in **K** from other time points will be normalized. On the other hand, there are theoretical problems with row normalizing at *all* time points. Row normalization transforms the scale of interaction based on the density of interaction reported at any given time point, and normalizations across many time points change the scale in as equally many different ways (as long as an actor’s density of interaction is changing). But as Burket (1984) noted in a debate over a similar issue—measuring rates of growth of knowledge (as opposed to rates of interaction)—one needs a constant metric, a single scale, in order to answer questions that are not purely normative in nature (e.g., “Does actor 1 influence actor 2 more than actor 3?”). In order to make valid inferences about changes in interactions over time, the metric of interaction should not change from time point to time point.

⁸This holds even if the absolute values of $\lambda_i k_{ii' t-1 \rightarrow t}$ are all less than unity because effects from i' to i accumulate through all paths linking i' to i , as indicated by the summations in Model (5).

⁹Note that Model (2) was based on the Markov principle that the state of the system at time t could be modeled as a function of the state of the system at time $t - 1$. The process captured in Model (10) is no longer Markovian in the sense that the state of the system (as defined by **Y** _{t}) must be specified in terms of the chain of interactions and errors emanating from each time point, instead of the state of the system at the immediately preceding time point. That is, evolution in the system cannot be predicted in terms of the state of the system at the previous time point. The system can be described as Markovian only if the system state is defined in terms of the maximum paths and all errors that have entered the system at previous time points.

¹⁰If we restate Model (11) as:

$$y_{it} = \delta \sum_{v=1}^t \sum_{i'=1}^N q_{ii' t-v \rightarrow t} e_{i' t-v} + \left[(1 - \delta) \sum_{v=1}^t \sum_{i'=1}^N m p_{ii' t-v \rightarrow t} e_{i' t-v} \right] +,$$

we observe the parallel with Friedkin and Johnsen’s (1997) Model (2).

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There is an effect of influence associated with all paths $q_{ii't-v \rightarrow t}$ that must be anchored. Friedkin and Johnsen used y_{j0} while we use $mp_{ii't-v \rightarrow t} e^{i't-v}$. If all exogenous effects after $t = 0$ are set to 0, then the only difference is that each actor's anchor in the Friedkin and Johnsen model is defined by the initial information to which *that actor* was exposed whereas in our model there is a common anchor for all actors defined by the initial information *in the system*.

¹¹Note that we could have accomplished a similar effect by assigning to some individuals a motivation to maintain the coherency of the organization or the system. Instead we have achieved our result by relying only processes that are motivated at the level of the individual.

¹²Only Carley (1990, 1991) has incorporated negative feedback in a system in which interaction, even though it may increase the amount of shared information between two individuals, does not always generate more interaction (Carley 1991, pp. 340–341). But Carley does not incorporate competing processes (such as the pursuit of information versus balance) that are explicitly defined for individuals or dyads in either of her models. Instead, the negative feedback in Carley's system is a byproduct of row normalization of the extent of interaction (as opposed to row normalization of the extent of influence), as an increase in the extent of shared information between two actors will not necessarily increase their rate of interaction because they may be pulled away from each other by more extensive commonalities with others. Carley's approach is dependent on restricting the extent to which actors can engage in interaction, and raises the question of why there is a common restriction on all actors. And if there is not a common restriction, then how do we determine which actors are allowed to interact more or less than others? The latter question can be answered only by directly incorporating factors which generate positive and negative feedback in the model of selection, as in Model (17).

¹³We chose the distribution of sentiment to have nonzero mean so that we could demonstrate that the effects we observe apply to systems which are not perfectly balanced in terms of the initial mean sentiment.

¹⁴Note that although our figures display only the changes in actors' sentiments, we discuss them in terms of changes in sentiment and the corresponding changes in the pattern of interaction.

¹⁵A similar result can be obtained for $n = 2$ without relying on obtaining the eigenvalues of **A**. Define $z_t^+ = y_{1t} + y_{2t}$ and $z_t^- = y_{1t} - y_{2t}$. Then we have $z_{t+\Delta t}^+ = (\alpha k + \gamma)z_t^+$ and $z_{t+\Delta t}^- = (\alpha k - \gamma)z_t^-$. Clearly z_t^+ diverges if $\alpha k + \gamma > 1$ which will be the case when $\gamma = 1$ and $\alpha k > 0$. Similarly, z_t^- converges if $0 < \alpha k - \gamma < 1$ which will occur when $\gamma = 1$ and $0 < \alpha k < 1$. The latter condition will hold if we restrict $k < 1/\alpha$, a reasonable restriction. Therefore $|y_1 - y_2|$ grows small as $(y_1 + y_2) \rightarrow \pm\infty$. The implication is that the system approaches the line defined by $y_1 = y_2$. We are indebted to JiQiang Xu for this observation.

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Accepted by Kathleen M. Carley; received July 2, 1997. This paper has been with the author for one revision.