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A Complex Adaptive Systems Model of Organization Change

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The study of complex adaptive systems has yielded great insight into how complex, organic-like structures can evolve order and purpose over time. Business organizations, typified by semi-autonomous organizational members interacting at many levels of cognition and action, can be portrayed by the generic constructs and driving mechanisms of complex adaptive systems theory. The purpose of this paper is to forge a unified description of complex adaptive systems from several sources, and then investigate the issue of change in a business organization via the framework of complex adaptive systems. The theory of complex adaptive systems uses components from three paradigms of management thought: systems theory, population ecology, and information processing. Specific propositions regarding the nature of dynamical change will be developed, driven by the complex adaptive systems model. Supporting evidence for these propositions is then sought within the existing management theory literature. In doing so, the complex adaptive systems approach to understanding organization change will be better grounded in domain-specific theory, and new insights and research areas will come to light.

KEY WORDS: organization development; management; agents; schema; organization learning.

INTRODUCTION

The prevailing paradigm of a given era's management theories has historically mimicked the prevailing paradigm of that era's scientific theories (Ackoff & Emery, 1972; Hayles, 1991). For example, most of science lead-

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ing up to this century was heavily influenced by the scientific principles of Newton, LaPlace, and Descartes (Capra, 1982). This paradigm held as principle that, for example, the natural state of a system was equilibrium and that departures from equilibrium would be damped out. Likewise, the approach by which a system was understood was reductionist and deterministic: through understanding the component elements of a system and the manner in which they interact, the future states of the system could (theoretically) be predicted (Bohm, 1957).

Management theories in the nineteenth and early twentieth centuries also held reductionism, determinism, and equilibrium as core principles—indeed, all of social science was influenced by this paradigm (Hayles, 1991). Management theorists such as Fayol, Mooney, and Urwick invented management control mechanisms that are based on the "organization as machine" metaphor (Morgan, 1986). Organizational direction is embedded in plans which are then deployed via planning, budgeting, and management-by-objectives systems. A centralized, bureaucratic structure is key in helping organization leaders determine proper actions and deploy instructions to the workforce. Control is explicit: monetary rewards and punishments are a common form of motivation.

Reductionism gave rise to ideas such as division of labor, the idea of task, interchangeability of parts, standard procedures, quality control, cost accounting, time and motion study, and organizational charts (George, 1968). Frederick W. Taylor was responsible for integrating these ideas with the concepts of the scientific method to design a coherent management philosophy. His principles of scientific management have great influence over management practice of today. Taylor brought analytical logic to management. Taylor's managerial principles (1911) were summarized into four points: (a) develop a science for each person's work, (b) train and develop the workperson, (c) heartily cooperate with others, and (d) divide work and responsibility between labor and management.

Taylor believed in a "social system determinism"—that management of the organization could be predictable if we understood the science of management (Dooley, Johnson, & Bush, 1995; Spencer, 1994). Taylor and others focused on describing work by its elemental tasks, and managing work as such. Under scientific management, work tasks are divided into basic skills, and training and standardized methods helped eliminate differences between peoples' performance. Organizational controls, such as budget, performance review, audits, standards, etc., are used as negative feedback mechanisms for maintaining equilibrium (Leifer, 1989; Spencer, 1994; Wheatley, 1992).

As science has progressed in the twentieth century and different paradigms of scientific thought have emerged, so have different paradigms of management theory. While current management practice is still deeply rooted in the mechanistic approach, it has also evolved and matured via concepts from other paradigms of thought. The purpose of this paper is to explore how one specific paradigm of modern science—complex adaptive systems—can be used to understand organizations and the nature of their change. The next section explores management theory from the perspectives of systems theory, population ecology, and information processing. Section three will explore the history of complex adaptive systems and how management theorists have used it to date. Section four forges a composite model of complex adaptive systems, and specific propositions regarding the behavior of complex adaptive systems are determined. These propositions are also translated into the domain-specific language of business systems, and supporting literature is cited. The concluding sections summarize the nature of complex adaptive systems change, a strategy for change, and design principles.

THREE PARADIGMS OF MANAGEMENT THEORY

Systems Theory

Systems theory and cybernetics developed as an important field in the 1940s, via the work of, e.g., Ashby (1958), von Bertalanffy (1968), and Wiener (1948). One of the key purposes of systems theory is to describe a system in such a manner that automated control mechanisms can maintain the system's behavior at some desired goal. Fluctuations from the outside (environment) force the system to adjust in order to maintain equilibrium, and negative feedback mechanisms dampen the effect of these fluctuations. Likewise, positive feedback mechanisms, which accentuate fluctuations, can be used to enhance and accelerate the effects of positive fluctuations.

Systems theory caused management theorists to see the organization as an "organism" (Morgan, 1986). Fluctuations or contingencies from the environment are adjusted to by organization change (Lawrence & Dyer, 1983). These environments coexist and to a large extent are created by the organization—the organization does not play a passive observational role (Weick, 1979). The nature of change can be strategic (e.g., offering new product lines), tactical (e.g., developing closer relationships with suppliers), or cultural (e.g., initiating employee motivation programs).

Contingency theory claims that the manner in which the organization is organized and functions must correspond to the nature of the environment which it finds itself in (Lawrence & Lorsch, 1967). In a study of many different types of firms, Burns and Stalker (1961) found that for organizations embedded in stable and certain markets (e.g., a textile mill), a mechanistic organizational form was more appropriate: standardized methods, hierarchical structure, clearly defined lines of authority, communication and decision making, and clearly bounded roles. For organizations embedded in unstable and uncertain markets (e.g., an electronics firm), a organic organizational form was more appropriate: informal and changing lines of authority, open and informal communication, distributed decision making, and fluid role definitions.

Other contingency studies have found similar results (e.g.,, McKelvey & Aldrich, 1983; Miles & Snow, 1978; Pfeffer & Salancik, 1978), showing contingency effects along the dimensions of environment, industry, strategy, structure, technology, employee commitment, key beneficiaries, and empirical configurations (Morgan, 1986). For example, Mintzberg (1979) and Miller and Friesen (1978) investigated structural contingency via defining five structural forms along the spectrum of mechanistic to organic (machine bureaucracy, divisionalized form, professional form, the simple form, and the adhocracy), and found that the fit between structural form and environment was key to organizational performance. A hybrid structural form—the matrix organization, which distributes personnel both along functional lines as well as within project-related clusters, has become a popular way of structuring in lieu of uncertain environments (Mintzberg, 1979).

In the organic metaphor, organizations evolve according to contingencies in the environment. Change typically enhances complexity via further differentiation and specialization (being able to handle a wider variety of tasks) and/or better integration (being able to handle tasks which are more complex in a more effective manner; Lawrence & Lorsch, 1967).

Population Ecology

Rather than viewing the organization as adapting to the environment in a planned way, "population ecology" believes that organizational attributes are tested in a Darwinian landscape, where firms with inferior structures and/or practices die in a resource-constrained competition (Hannan & Freeman, 1989). Variation in organizational attributes occur in random and planned fashion, and variations which are beneficial are retained.

Variation is induced by institutionalized experimentation, direct and indirect incentives, and playfulness; selection is a purposeful managerial choice of action, based on pre-established goals, values, criteria, checkpoints, or competition; useful variations are retained via standardization and oversight via institutional controls, and internal interpretive schema change accordingly. The cycle of variation-selection-retention continues on. This broader view of change allows one to see an organization's change trajectory in light of larger, systemic issues. For example, several studies have shown that the organization and its corresponding technology co-evolve, each affecting one another over time (Rosenkopf & Tushman, 1994; Van de Ven & Garud, 1994).

The ecological view also generates a hereditary perspective on organizational behavior. Organizational traits can be transmitted vertically forward (e.g., old to young), vertically backward (e.g., young to old), or horizontally (e.g., young to young) (Baum & Singh, 1994). While the organizational inheritance process is more complex than its biological counterpart, positive (e.g., McKelvey, 1982) and negative (e.g., Csanyi, 1989; DiMaggio & Powell, 1983) traits have been observed to linger on in an organization well beyond any member's stay. Much transmission occurs within short time frames, because of the ease of iteration and the short expected lifetime (Cavalli-Sforza & Feldman, 1981).

Population ecologists have often modeled organization change as the diffusion and adoption of both technical and managerial innovations. The basic models describing the diffusion process can be characterized by S-shaped logistics growth curve. These curves describe a rapid initial growth and a subsequent saturation (or decline) of use. They are based on the assumption of "substitution," namely, growth in a new technology is linked to decline of the old, and technologies compete in the environment of a single, identified need (Cavelli-Sforza & Feldman, 1981). These models are based on the assumption that information spreads in an infectious manner via personal contact (Kodama, 1995). Because of pressures toward isomorphism, personal contact may lead to imitation of others within and outside the organization (Kanter, Stein, & Jick, 1992). In such a model, the likelihood of adoption increases as the number of other "users" increases, until usage is "saturated."

Davies (1979), Stoneman (1983), and Kodama (1995) have proposed that the dynamics of innovation adoptions can be better described by assuming that resistance to adoption is caused by institutional (inter- and intra-organizational) factors rather than an individual's risk aversion or propensity to imitate. In this model, adoption of the innovation co-evolves with the organizational environment needed to nurture the innovation (Van de Ven & Garud, 1992).

The innovation is adopted by only a few individuals at first, because it is economically advantageous to only a few individuals at first. The individual makes a behavioral decision of adoption when some "critical" value has been surpassed (mathematically, a "probit model" emerges). In some cases, this critical value may be the ratio between the expected "pay-off period" and the desired pay-off period; the exogenous variable(s) behind the "critical value" needs to be formulated in each particular case.

Thus, the co-evolutionary model differs in that rather than modeling adoption as an exponential growth over time, it models growth in terms of consequent change in some exogenous factor(s) in the organizational environment. Dynamically, it may be best described by the dynamics of punctuated equilibrium (Tushman & Romanelli, 1985; Anderson & Tushman, 1990).

Innovation diffusion and adoption can also be viewed via a neo-Darwinian evolutionary model, where innovations are treated as memes (cultural genes, e.g., Dawkins, 1976), fitness is determined not only by monetary influx but also by the extent to which the innovation competes for the consciousness of society's members, and the dynamics of innovation diffusion are best described by models of organic, self-organizing systems. Various mathematical models have been developed for the vertical, oblique, and horizontal transmission of cultural traits (e.g., Cavelli-Sforza & Feldman, 1981). These have been applied to study phenomena such as bias transmission from leaders (e.g., Boyd & Richerson, 1985) and meme–gene coevolution (e.g., Lumdsen & Wilson, 1981). In the case of cultural transmission between "parent" (vertical) and "teacher" (horizontal), the (single) parent can be represented by a so-ranked organizational superior (e.g., supervisor), while a teacher can be represented by a colleague (superior, peer, or inferior) who has great influence over other individuals. The mathematical model shows that "transmission through a social leader or teacher results in greater homogeneity in a population" (Cavelli-Sforza & Feldman, 1981, p. 339) than transmission through a parental figure. The parental figure, however, can have a long-lasting effect: the culture created by the organization's initial leaders forms a "genetic imprint" for the organization's ontogeny; it will be clung to until it becomes unworkable or the group fails and breaks up (Donaldson & Lorsch, 1983; Schein, 1992).

Information Processing

At the same time that systems theory was being developed, science was developing better understandings of the human brain and its associated cognitive mechanisms. Simon (1947) and others (e.g., Gailbraith, 1974; March & Simon, 1957) explored the parallel between human and organizational decision making. Simon's concept of bounded rationality posits that since individuals are limited in their information-processing capabilities, so too are organizations: organizations act on incomplete information, explore a limited number of alternatives, and do not necessarily develop accurate cause and effect maps of reality; heuristics dominate organizational decision making and thus organizational change.

Gailbrath (1974) considered the manner in which organizations adapt to complex, uncertain environments by changing their information-processing capabilities, either by reducing the need for information (making tasks and subgroups more autonomous, or creating slack resources) or by increasing the capacity for information acquisition, storage, and retrieval (via information systems).

There are four steps by which the organization acquires knowledge and learns: knowledge acquisition, information distribution, information interpretation, and organizational memory (Huber, 1991). Through such learning, organizational members, individually and collectively, perceive the environment around them and take subsequent action. Learning and change may often be considered dual. Argyris and Schon (1978) differentiate two types of learning: first (or single-loop) and second (or double-loop) order. An individual's mind stores patterns which govern interpretation and action as schema; these schema are limited in their realism in the same way that we understand decision-making to be rationally-bounded (Kielser & Sproull, 1982). First-order learning involves comparison between a perception and an expectation (via the schema); errors are corrected in a simple, cybernetic way through negative feedback. Most problem-solving hinges on first-order learning: a problem is perceived as such because the current, observed organizational state does not match the expected, desired state. Appropriate corrective action is taken.

Second-order learning involves active manipulation and change of the interpretive schema. One barrier toward such learning is that high skill in first-order learning—leading typically to rewarded performance and promotion to managerial ranks—can actually detract from the ability to perform second-order learning (Argyris, 1991). The nature of schema change, etc. will be discussed in much greater detail later.

Schon (1975) also identified deutero-learning as an important skill—the ability to learn how to learn. At a general level, this could include learning how to: make schema explicit, seek data to test schema, confront the actual schema ("theory-in-use") with the publicly stated schema ("espoused theory"), and a focus on dilemmas (Schon, 1975). In a more specific example, organizations have learned how to improve one of their key learning strategies—total quality management—through the use of structured comparison to prescribed learning systems, e.g., via Malcolm Baldrige National Quality Award; Dooley, Bush, Anderson, & Rungtusanantham, 1990; Garvin, 1991) and the ISO 9000 criteria (Lamprecht, 1992) and benchmarking other "learning systems" (Camp, 1989).

Three types of organization change models have been discussed: organic (systems theory), organismic (population ecology), and cognitive (information processing and organizational learning). Others obviously exist (e.g., cultural, political, psychic, dialectic, and domination metaphors; Morgan, 1986). These three, however, supply the key elements of the complex adaptive systems model of organization change: agents scan the environment and adapt accordingly (organic), using schema to interpret reality and context, and trigger decisions and actions (cognitive), while competing and cooperating with other agents for resources and information (organismic).

COMPLEX ADAPTIVE SYSTEMS

Basic Elements

The complexity paradigm uses systemic inquiry to build fuzzy, multivalent, multilevel and multidisciplinary representations of reality. Systems can be understood by looking for patterns within their complexity, patterns that describe potential evolutions of the system. Descriptions are indeterminate and complimentary, and observer-dependent. Systems transition naturally between equilibrium points through environmental adaptation and self-organization; control and order are emergent rather than hierarchical (Dooley *et al.*, 1995; Lewin, 1992; Waldrop, 1992).

Core epistemological concepts from the mechanistic era were seriously challenged by Einstein's theory of relativity, and by the discovery of quantum mechanics (Bohm, 1957; Gribbin, 1984). As Kuhn (1970) points out, while paradigmatic revolutions are discontinuous change, they typically do not occur at one instant in time. Instead, "change occurs through negotiations at multiple sites among those who generate data, interpret them, theorize about them, and extrapolate beyond them to broader cultural and philosophical significance" (Hayles, 1991, p. 4). The language of the old paradigm is likely to be used in the new paradigm, causing further confusion (Hayles, 1991, p. 4; Kuhn, 1970, p. 149). In the Newtonian paradigm, for example, equilibrium is considered the natural state of the system (Kellert, 1993); in the complexity paradigm, equilibrium is just one of several states possible—whether equilibrium is natural is situational.

A theory of complex adaptive systems was borne from the discovery of chaotic dynamics in systems' behaviors. Chaos theory has developed along two dimensions. Experimentalists (as popularized in Gleick, 1987) found ways (primarily grounded in topology) to discover deep and complex patterns in seemingly random or "chaotic" data. Prigogine and Stengers (1984), among others, use chaos to describe how order can arise from complexity through the process of self-organization. Here is a summary of some of the main characteristics of systems described by chaos theory (Dooley *et al.*, 1995): (a) seemingly random behavior may be the result of simple nonlinear systems (or feedback-coupled linear systems), (b) chaotic behavior can be discovered via various topological mappings, (c) nonlinear systems can be subject to sensitive dependence to initial conditions—this sensitivity forces a re-examination of causality—which now must be considered multilevel and multideterminate (Abraham *et al.*, 1990), (d) systems that are pushed far-from-equilibrium (at the edge of chaos) can spontaneously self-organize into new structures, and (e) changes in the essential nature of a system take place when a control parameter passes a critical threshold—a bifurcation point.

While the concepts of chaos and self-organization have evolved from the physical sciences, the notion of complex adaptive systems (CAS) has its roots in the biological sciences (Gell-Mann, 1994). Whereas chaos theory relates to a particular behavior of complex systems, complex adaptive systems theory allows one to analyze the organizational system from a more holistic point of view. A CAS is both self-organizing and learning; examples of CAS include social systems, ecologies, economies, cultures, politics, technologies, traffic, weather, etc.

Autopoiesis

The first managerial applications of complexity theory were driven by Maturana and Varela's work on autopoiesis. In the theory of autopoiesis (Maturana & Varela, 1992), structural change occurs through self-renewal (replication, copy, and reproduction). This self-production produces a history of change: "Ontogeny is the history of structural change in a unity without loss of organization in that unity. This ongoing structural change occurs . . . either as a change triggered by interactions coming from the environment in which it exists or as a result of its internal dynamics . . . . The overall result is that the ontogenic transformation on a unity only ceases with its disintegration . . ." (p. 75). The ontogeny of the autopoietic system is contained in its internal components and their interactions; the environment only triggers change; the possible futures are encoded inside the system at the time of trigger (Maturana & Varela, 1992). This is in marked departure from previous organic models of organizations, which modeled the interface between organization and environment as more open.

Wheatley (1992) recognizes the bridge between the companies focused on core competencies (Prahalad & Hamel, 1990) and autopoietic organizations. She states that by structuring around skills instead of business units, new business opportunities can be more rapidly responded to; such organizations exemplify the nature of the autopoietic system to be highly self-reflective (but not ego-maniacal).

System Dynamics

A second avenue for studying organizations as complex systems was via the work of Forrester (1961) in system dynamics. The purpose of system dynamics was to use simple differential equations—as used in the cybernetic control of electromechanical systems—to model large-scale systems, including economies (Roberts, 1963), social organizations (Simon, 1952), and culture (Levin, Hirsch, & Roberts, 1972). Complexity, in the form of "surprising behavior," was found in many of these studies. Most users of system dynamics models still do not incorporate nonlinear behavior into their models; as mentioned before, CAS are typified by nonlinear flows of information and resources. As such, these linear dynamical models typically fall short of discovering truly complex behavior. There have been a number of researchers (e.g., Allen & Sanglier, 1981) who have used cellular automata-type simulations instead of system dynamics, and have discovered the complex clustering phenomena found in CAS.

Dissipative Systems

Prigogine and Stenger's work on dissipative systems (1984) inspired a number of management writers to posit how the theory of far-from-equilibrium systems could be used to describe, and perhaps prescribe, organization change (Guastello, Dooley, & Goldstein, 1995). Leifer (1989), among others, recognized that far-from-equilibrium conditions can be generated by trigger events such as crises (e.g., impending competitive death of Xerox) or leader-declared revolutions (e.g., GE's Jack Welch) (Tichy & Ulrich, 1984). Unlike first-order adaptations, these crises overwhelm the organization's normal capacity for change. At times, the leader may even invoke artificial crises, such as through creation of a challenging vision, in order to move the system away from equilibrium (Nonaka, 1988).

Far-from-equilibrium conditions tend to create a dynamic stability where paradox abounds. The paradoxical nature of CAS—between randomness and order, freedom and control, learning and unlearning, adaptation to the environment and construction of the environment—has not gone unrecognized. Wheatley (1992) and Stacey (1992) advocate purposeful surfacing of these tensions, in order to generate far-from-equilibrium conditions which will hopefully lead to creative new solutions. Stacey goes so far as to say that a manager's job is to allow political forces to challenge one's own source of power and control—the tension between the mechanistic management of the status quo and the organic management of the learning organization allow the system to thrive. Dooley *et al.* (1995) have pointed out the paradoxical nature of total quality management programs, with the simultaneous focus on control and learning.

Goldstein (1990, 1994) has developed specific techniques for moving a group "far-from-equilibrium"; once there, the potential for re-organizing around a new mode of behavior can be realized. Of course, one cannot control the end result of the self-organization; it can only be influenced by shared value and purpose (Dooley *et al.*, 1995). Goldstein advocated the following ways of generating far-from-equilibrium conditions in business organizations: (a) work with (define, discuss, change) organizational boundaries; (b) connect the system to its environment (customers, suppliers, competition); (c) difference questioning (seek divergence in group discussion; method based on similar approaches first developed in family systems therapy (Palazzoli, Boscolo, Cecchin, & Prata, 1980); (d) purpose contrasting (heightening awareness of the state gap; Kiesler & Sproull, 1982); (e) challenge self-fulfilling prophecies; (f) challenge assumptions creatively (e.g., Argyris & Schon, 1978); (g) develop nonverbal representations of the system, such as Morgan's (1986) "imaginization"; and (h) take advantage of chance (e.g., statistical methods which generate knowledge via outliers).

Eoyang (1993) has developed tools which help accentuate differences in systems, particularly across organizational boundaries. Group communication patterns are diagnosed into a 2 × 2 matrix corresponding to the dimensions of high or low transfer of information, and high or low differentiation; self-diagnosis is employed. Others have employed organizational "games" to develop (at least) self-reflection, if not far-from-equilibrium conditions (e.g., Guastello, 1995).

Chaotic Dynamics

A number of writers have focused on the "chaotic" nature of a change event. Tushman, Newman, and Romanelli (1986) noted that successful, large-scale organizational change was typically followed by prolonged periods of stasis, or incremental change. In CAS terms, this phenomena is called "punctuated equilibrium" and it has roots in the evolutionary studies of ecologies (Gould, 1989). Similarly, Gershick (1988) found that work teams go through similar developmental stages: inertia and revolution in attitudes and behaviors alternated, often triggered by real and perceived deadlines. The key theme in punctuated equilibrium is that second- (or in some cases, third) order change does not need to be invoked by catastrophic events. Change occurs when the system has evolved far-from-equilibrium, which could come from an accumulation of small perturbances or the cascading, compounding effect of a small disturbance while the system is hypersensitive to such disturbances (e.g., operating in a chaotic regime of behavior).

The unpredictability of CAS systems, especially when they are in chaotic regimes of behavior, has been noted by strategic management writers (Cartwright, 1991; Kiel, 1994; Levy, 1994; Mintzberg, 1994; Stacey, 1992; Wheatley, 1992; Zimmerman, 1993). Stacey advocated an open-ended planning process, whereby strategic issues are formulated and then exposed to divergent thinking and group dialogue.

A number of researchers have explored organizational change in a more quantitative fashion by applying the statistical modeling techniques of nonlinear dynamical systems (e.g., fractal dimension, Lyapunov exponent; Peitgen, Jurgens, & Saupe, 1992) to organizational performance data. The goals of such analyses are to: (a) determine whether apparently random data has embedded structure, (b) determine the complexity of the system (the fractal dimension of the data's attractor corresponds to the (sub)system's degrees of freedom), (c) potentially develop short-term predictive models, and (d) explore nonlinear causalities. A number of studies in different areas have been done: Guastello (1995) has examined a multitude of organizational phenomena, including decision making, stress and human performance, accidents, creativity, and group development. Priesmeyer (1992) used phase plane analysis to look at applications in marketing, finance, and production. Kiel (1994) looked at nonlinear relationships (in public management) between work effort and service requests. Gresov, Haveman, and Oliva (1993) used catastrophe models (Guastello, 1995) to study the nature of strategic competitive response. Numerous studies have looked at chaotic dynamics in economics (see Guastello, 1995).

In order to demonstrate the type of analyses being attempted, works investigating the dynamics of production systems will be detailed here. Chase, Serrano, and Ramadge (1993) have found possible evidence for nonlinear, chaotic conditions in a simple, deterministic, switched-flow model. Huberman and Hogg (1988) have found point, periodic, and chaotic attractors in scenarios relating to distributed production control systems. Lin and Solberg (1987) observed chaos in the production rate of an assembly system when a delay is increased.

Beaumariage and Kempf (1994) have done a series of experiments using a simple, deterministic manufacturing system model. It consists of four machines and four part types, and some simple part arrival, batching, and scheduling rules. They have found eight and ten distinct attractors (looking at interdeparture times) in two different models. The attractors are periodic, ranging in periodic length from six to 1278. By changing some simple parameters, e.g., the release size, they observed changes in both period length and shape. Small changes in queue content, at certain times, were shown to create great changes in output performance, and indeed even shift the system from one attractor to another. It is not clear whether this sensitivity to initial conditions is in fact exponential in nature, which would be a prerequisite to indicate chaos (as opposed to complex periodic behavior).

Deshmukh (1993) observed part interdeparture times from a multimachine workcenter under three different sequencing rules, shortest processing time (SPT), longest processing time (LPT), and first in first out (FIFO). An analysis of return maps, indicates that the FIFO rule induces chaos in the output process while LPT results in periodicity. Periodicity was found to be particularly useful in reducing system performance variance.

For general queuing systems, Erramili and Forys (1991) have found periodic and chaotic attractors in a model of a telephone switching system. Leland, Taqqu, Willinger, and Wilson (1993) claim to find fractal-like structure in ethernet traffic.

Dooley (in press) simulated a simple manufacturing system and discovered low dimensional chaos in the throughput times of the simulated production facility. Chaos appeared more likely in congested systems whose scheduling schemes do not alter queue rank. The distribution of throughput times resembles the dual-mode distribution generated via the mushroom catastrophe dynamics (Guastello, 1995). A return map of the data, shown in Fig. 1, shows the strange attractor indicative of chaotic behavior.

The area of organizational innovation has also been one studied in some detail, in terms of change dynamics. The process of innovation has been characterized as "being inherently uncertain, dynamic, and a . . . random process" (Cheng & Van de Ven, 1994; cf. Jelinek & Schoonhoven, 1990). Individual, chance events play a large role in the discovery process.

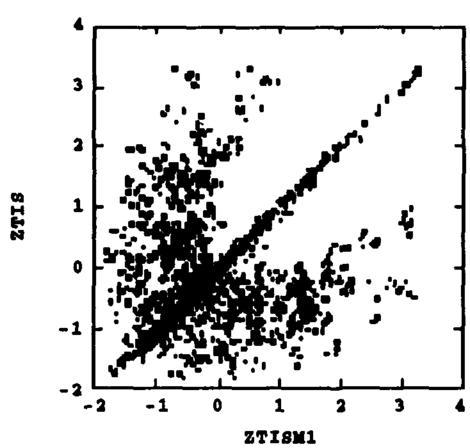

Fig. 1. Chaotic behavior in a manufacturing system.

History is littered with inventions brought about by a researcher's "mistake" (e.g., post-it notes). Yet there is evidence that some degree of order may exist, implicit to the observed randomness, suggesting that such systems are operating at the edge of chaos (i.e., they have chaotic dynamics of low-dimensional order).

Cheng and Van de Ven (1994) and Koput (1992) have found numerical evidence for chaos at the beginning of the innovation process. Leonard-Barton (1988) found evidence for a "nonlinear process involving complex recursive cycles of adaptation" (Jayanthi & Sinha 1994) in a series of case studies. The studies of Tyre and Orlikowski (1994) suggest that random events in the innovation process trigger adaptive cycles. Jayanthi and Sinha (1994) have also found numerical evidence of chaos in the activities bridging innovation and production.

CAS AND ORGANIZATION CHANGE: THEORETICAL PROPOSITIONS

An important analysis of chaos and organization theory was recently performed by Thietart and Forgues (1995). Many of the ideas presented in this paper can also be found in that paper; the authors developed six main propositions:

1. Organizations are potentially chaotic.
2. Organizations move from one dynamic state to the other through a discrete bifurcation process (second-order change).
3. Forecasting is impossible, especially at a global scale and in the long term (unpredictability).
4. When in a chaotic state, organizations are attracted to an identifiable configuration (order out of randomness).
5. When in a chaotic state, similar structure patterns are found at organizational, unit, group, and individual levels (fractal nature of chaotic attractors).
6. Similar actions taken by organizations in a chaotic state will never lead to the same result.

The authors state that the organization may enter a chaotic state when system variables are highly coupled, system variables follow different periodic patterns, and the system is composed of a large number of counteracting forces. One subtle yet important distinction that must be made is that chaotic behavior is not an attribute of the system per se; rather, chaos is an attribute of some aspect of the system's behavior (Kellert, 1993). The state of the system can be described by numerous performance characteristics. The chaotic behavior of one characteristic (e.g., the firm's daily stock value) is not an indication that other characteristics will behave similarly (e.g., the firm's productivity levels). In fact, chaotic behavior is not even guaranteed to remain constant across scale (Mandelbrot, 1983); while daily stock prices may vary chaotically, weekly prices may vary periodically (Peters, 1991). That said, propositions 2–6 remain true in the more general case of a CAS. The general state of far-from-equilibrium conditions present in living systems is enough to engage these propositions.

Before business organization-specific propositions can be developed, a generic model of CAS must be presented. Such a model does not exist. A number of people have put forth particular models of complex adaptive systems: Gell-Mann (1994), Holland (1995), Jantsch (1980), Maturana and Varela (1992), and Prigogine and Stengers (1984). The essential principles of CAS has been taken from each of these works and synthesized into a single description.

A CAS behaves/evolves according to two key principles: order is emergent as opposed to predetermined, and the state of the system is irreversible and often unpredictable. One way to demonstrate this property of emergence is to visually study cellular automata (CA) (Prigogine & Stengers, 1984). CA is the computer-simulated embodiment of a complex (although not necessarily adaptive) system; this demonstration will also help introduce some of the basic behavioral engines in CAS.

Two-dimensional CAs are represented by a grid of cells (in the computer each cell is defined to correspond a particular number of pixels in size), and the state of each cell, in the simplest case, is binary. In a computer simulation, the state of the cell in the succeeding moment is determined by the state of the cell in the previous moment, as well as the state of neighboring cells in the previous moment. On the computer, each binary state (e.g., on or off) can be represented by a color (e.g., white=on, black=off), and the state of all cells is updated during each iteration.

Figure 2 shows a CA whereby the middle cell behaves according to the rule: if three of less of my neighbors are "on," turn "off"; otherwise, turn "on." In this case, since only three of the neighbors are "on," the middle cell turns "off." To demonstrate the emergence of order in a complex system, a large grid is generated and filled randomly: 50% of the cells are "on," and an equal number "off," although in no spatial pattern whatsoever. The grid on the right of Fig. 3 represents this (these figures were generated using the software program *CASim*; Karakatsios, 1990). Next, each cell is allowed to evolve according to a simple behavioral rule, called vote (Karakatsios, 1990). If three or less of your neighbors (including yourself) are on, turn off; if six or more are on, turn on. This is simple majority rule. The twist is near the tie: If four neighbors are on, turn on; but if five

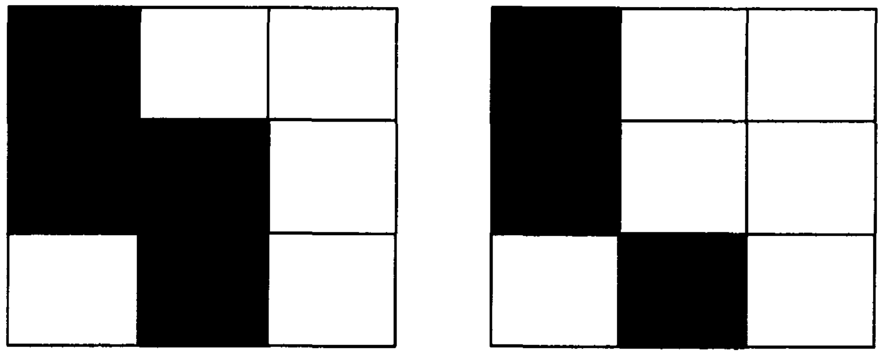

Fig. 2. Two dimension CA at time T and T+1.

neighbors are on, turn off. The CA is in a torus formation—cells at the edges are neighbored to their companion cells at the opposite edge. The figure at the right shows the system after a dozen iterations. Out of the randomness, the system has equilibrated at a complex yet definable order (the system has generated fractal boundaries of a sort, which is typical in CAS (Eoyang & Dooley, 1996).

The other characteristic of CASs is that they are irreversible and unpredictable (Gell-Mann, 1994). The nature of change is dynamical—that is, not only does a given entity within the system change over time, but so do the entities around it, and the external "environment." This leads to a general, unidirectional evolution. The larger number of degrees of freedom

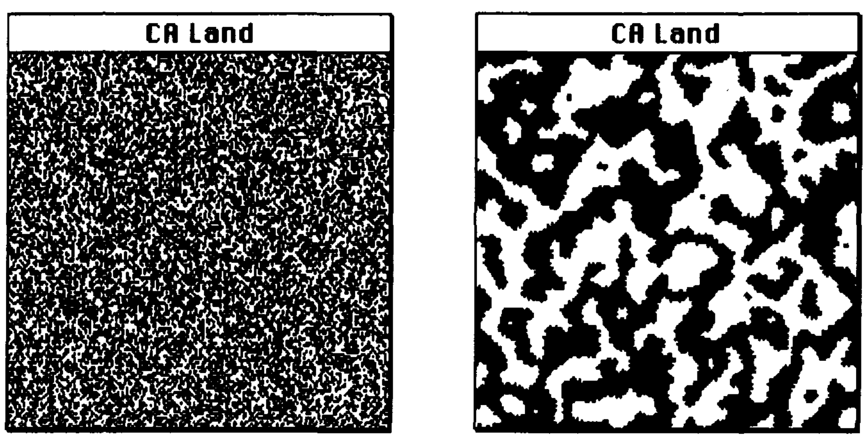

Fig. 3. Order out of randomness in a complex system.

in the system make it impossible to predict ahead of time what might happen; the quickest way to predict the future of a complex system is to let it evolve and see what happens. The "unpredictable" component of CAS stems from the fact that often a particular operating characteristic is behaving chaotically. In a chaotic system, prediction is impossible because small errors in initial specifications grow exponentially and destroy the validity of the final prediction (Peitgen *et al.*, 1992). Given those two general principles, a more detailed description of CAS is given.

The basic building blocks of the CAS are agents. An agent in a biological system is a cell; in an economic system, a seller or buyer; in a cultural system, a meme; in an organizational system, an individual. Different agents can be defined at different scales. Agents are semi-autonomous units which seek to maximize some measure of goodness, or fitness, by evolving over time. Agents scan their environment—which includes both other agents within the CAS as well as the external environment—and develop schema representing interpretive and action rules. These schema often depend on building blocks, so that one schema may actually be composed of several smaller, more basic schema. For example, a schema involving "how to dress when it is cold out" would necessarily involve a building block which states "it is uncomfortable to be cold." In an organizational system, building blocks occur in the form of general attitudes toward other function areas (e.g., labor vs. management), values, symbols, myths, business assumptions, etc.

These schema are rational bounded: they are potentially indeterminate because of incomplete and/or biased information; they are observer dependent because it is often difficult to separate a phenomenon from its context, thereby identifying contingencies; and they can be contradictory. Even though observations which negate existing schema will tend to be discarded, competing schema can evolve concurrently and may not be logically inclusive of one another. For example, a person can "distrust bankers," but still instill trust in an individual who happens to be a banker but also a close friend. In organizational systems, strategies, goals, and values often conflict with one another, leading to dialectic struggle (Morgan, 1986). The source of conflict is not necessarily intended; one might argue that conflicts and paradoxes are the fodder of organizational creativity.

Schema exist in multitudes and compete for survival. Existing schema can undergo three types of change: first-order change, where action is taken in order to adapt the observation to the existing schema; second-order change, where there is purposeful change in the schema in order to better fit observations; and third-order change, where a schema survives or dies because of the Darwinian survival or death of its corresponding CAS. In organizational systems, numerous researchers have identified the natural existence of first- and second-order change (e.g., Argyris & Schon, 1978; Fiol & Lyles, 1985; Lant & Mezias, 1992; Levitt & March, 1988). Population ecologists (e.g., Hannan & Freeman, 1989) have readily identified third-order change in organizations.

Schema can change through random or purposeful mutation, combination (genetic cross-over) with other schema, or acquisition of other building blocks. Organization learning theorists have identified specific strategies related to "genetic change" (Huber, 1991): congenital learning (cultural transmission from other members), experiential learning (via planned experimentation, self appraisal, and learning curves), vicarious learning (e.g., benchmarking other organizations' process, systems, and results), and grafting (e.g., acquisitions and mergers, strategic alliances and partnering, and migration of top management).

Schema change generally has the effect of making the agent more robust (it can perform in light of increasing variation and variety), more reliable (it can perform more predictably), or grow in requisite variety (in can adapt to a wider range of conditions; Arthur, 1994). At the metalevel of the organization, "excellent" organizations often exclusively choose one of three strategic pathways: customer intimacy—providing holistic and value-added sets of services and products (robustness); operational excellence—providing volume and certainty in quality, while reducing internal costs (reliability); or product innovation—inventing new products to fill new market niches (requisite variety; Treacy & Wiersema, 1995).

Schema survival and/or change is not always beneficial to the agent. Schema may adapt to a local optimum (Kauffman, 1995) and become deeply ingrained and difficult to alter, thus representing a maladaptation over the long run (Gell-Mann, 1994). The "QWERTY" keyboard is an oft-quoted example of such maladaptation (Arthur, 1994).

Schema define how a given agent interacts with other agents surrounding it. As agents aggregate into meta-agents, schema can follow, so that whole subunits of the CAS can be differentiated by common schema within, but differentiated schema outside of the subunit. In general, there is consensus within an aggregate about mission, strategy, goals, means, measurement, and correction. In order to create such an environment of consensus, leaders create common language and conceptual categories, define group boundaries and criteria for inclusion and exclusion, distribute power and status, develop norms for intimacy and friendship, define and allocate rewards and punishments, and explain the unexplainable. Shared schema define the culture of the organization, and incorporate assumptions about the nature of truth and reality, the nature of time, the nature of space, the nature of human nature, the nature of human activity, and the nature of human relationships (Schein, 1992).

As organizational members become more cohesive and integrated over time, there is a tendency for first-order learning to predominate over second-order learning (Virany, Tushman, & Romanelli, 1992). Habit, institutionalization, and history drive out deep problem solving. Experimentation by organizational aggregates tends to decrease over time. Studies on "executive succession" have found that second-order learning can be facilitated by such change-over (Virany *et al.*, 1992).

The fitness of the agent is a complex aggregate of many factors, both local and global. The general health or fitness of the agent determines what the probability of change will be. In humans, self-discrepancy theory (Wiggins, 1987) predicts that if an individual's current state does not match their ideal state, the discrepancy represents that one of the absence of positive outcomes, and the person is likely to be vulnerable to dejection-related emotions, disappointment and dissatisfaction. If, on the other hand, the discrepancy lies between the perceived self-state and one's perception of what some other individual's (friend, superior, spouse) expectations are, agitation-related emotions are likely, leading to fear and feeling threatened. Dejection is likely to lead to second-order change; agitation is likely to lead to defensive maneuvers and first-order adaptation.

Optimization of local fitness allows differentiation and novelty/diversity; global optimization enhances the CAS coherence as a system and induces long-term memory. The interplay between the two is dynamical, and in terms of outcomes, often unpredictable. The fitness of a particular schema is attributed to the fitness of the agent, so that unfit agents will tend to undergo second-order change in schema.

In general, the probability of second-order schema change, as given by the probabilities of mutation, cross-over, and acquisition, are a nonlinear function of the fitness value (shown in Fig. 4). Below a certain threshold level, change is unlikely and fluctuations are dampened. Above the threshold value, change is imminent and fluctuations are magnified; neuronal behavior follows this pattern (deBono, 1969). In human systems, studies of managers making decisions determined that simple thresholds are typically used to differentiate action from inaction (aspiration theory; Cyert & March, 1963; Kiesler & Sproull, 1982).

In Prigogine and Stenger's theory of self-organization (1984), fitness corresponds to an equilibrium condition: far-from-equilibrium conditions correspond to low fitness. It is at these far-from-equilibrium conditions that complex systems can spontaneously evolve new and more complex structures of order. The system does so through self-organization, which is triggered by random fluctuations which cascade exponentially through the system. Two prototypical examples have been often used from Prigogine and Stengers' work (1984). The Benard instability is represented by a dou-

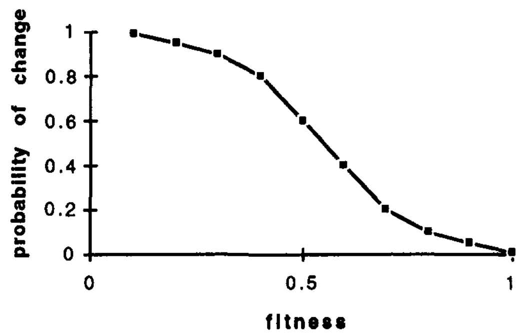

Fig. 4. Change in probability as a function of fitness.

ble cylinder jar. Heating causes a differential temperature gap, and a thermal gradient rises vertically across horizontal layers. Prior to a threshold value, stability is maintained while heat only flows via conduction. Past the threshold, convection forces arise from molecular coherence (i.e., via an increase interconnectedness) and ordered large-scale (hexagonal) structures emerge. In the aggregation of cellular slime mold, spores multiply through unicellular reproduction and grow until food (e.g., bacteria) becomes scarce. Reproduction is paused and after a time cells begin to emit chemical signals. The spores follow these signals and self-organize into an aggregate capable of migration. When developmental thresholds are met, the aggregate differentiates into a stem and fruiting body and spores are put forth.

The nature of agents, schema, and schema change have been identified. Finally, one must understand how agents interact with each other inside (and outside) the boundaries of the CAS. The driver behind these interactions, as demonstrated by the cellular automata model, are schema which define interpretive and action rules. Actions involve the exchange of information and/or resources. These flows may be nonlinear; for example, it may take two units of resource A to produce one unit of resource B, but it may take six units of resource A to produce an additional unit of B. Information and resources can undergo multiplier effects—their impact can increase in a nonlinear fashion and cascade throughout the system—based on the nature of interconnectedness in the system.

Tags help identify what other agents are capable of transaction; tags also facilitate the formation of aggregates, or meta-agents. Meta-agents help distribute and decentralize functionality, allowing diversity to thrive and specialization to occur. In organizational systems, distributed and decentralized control enhances reaction speed and robustness, diversity ensures robustness and creativity, and specialization enhances requisite variety (Kelly, 1994). For example, hierarchy (e.g., managers) and function (e.g., sales) are common organizational tags. Cultural (e.g., gender, educational background, race, age) and role (e.g., leader, negotiator, organizer) differences also may act as organizational tags.

Agents or meta-agents also exist outside the boundaries of the CAS, and schema also determine the rules of interaction concerning how information and resource flow occurs. In an organizational system, such external meta-agents would include customers, competitors, suppliers, regulators, government, and the surrounding community.

Table 1 gives a specific list of behaviors that define CAS which are subsequently developed into specific propositions about the nature of change and adaptation in business organizations. From these, Table 1 shows the propositions in terms of business organizations, and an illustrative citation.

CONCLUSIONS

The Nature of Change

The only true statement that could be made about the nature of change in a CAS is that there is not necessarily a consistent pattern of change. Change may occur rapidly or slowly; it may accumulate linearly or nonlinearly; it may be constant or have bursts of punctuated equilibrium; it may be resisted or encouraged; it may take little or many resources; it may have a profound or no effect on system outcomes. In general though, we see organizations get better at what they already do (first-order change), change what they do (second-order change), and persist or die (third order change). Changes will tend to send the system's performance characteristics into trajectories which are stable, periodic, chaotic, or random.

Strategy for Change

Teleology posits that organizational members develop toward an end goal or state (Van de Ven & Poole, 1995). Knowledge of the current state is partially determined by organizational identity, a powerful and deeply ingrained schema (Fiol & Huff, 1992; Reger, Gustatson, Demarie, & Mullane, 1994) that individuals in the organization possess; they use such schema to interpret action (Dutton & Dukerich, 1991). The strength of these schema are dependent upon such things as work history, tenure with current firm, and level of satisfaction with previous and current jobs. An organization's actual state is essentially hidden in its complexity as a whole from any single person's view, exceeding human perceptual, intellectual,

Table 1. CAS and Organizational Change

General principles	
1. Organizational order is emergent.	Population ecology theories of organization change (Hannan & Freeman, 1977)
2. Organizational states are irreversible.	Life cycle theories of organization change (Van de Ven & Poole, 1995)
3. The future states of the organization are relatively unpredictable.	Open-ended strategic planning (Mintzberg, 1994)
Schema and agents	
4. Organizational members scan the environment and develop schema.	Information-processing theories of organization change (Simon, 1947)
5. Organizational schema are often built from existing building blocks.	Cognitive chunking (Kielser & Sproull, 1992)
6. Organizational schema can be indeterminate, observer dependent, and contradictory.	Bounded rationality (March & Simon, 1957)
7. Organizational schema undergo first-, second-, and third-order change.	Single and double loop learning (Argyris & Schon, 1978); population ecology theories of organization change (Hannan & Freeman, 1989)
8. Organizational schema change via mutation, combination, and acquisition.	Organization learning (Huber, 1991)
9. When organizational schema change, requisite variety, robustness, and/or reliability is enhanced.	Strategic change (Treacy & Wiersema, 1995)
10. Organizational schema define rules of interaction with other agents.	Organizational culture (Schein, 1992)
Agent fitness	
11. An organizational member's satisfaction is a complex aggregate of local and global issues.	Organizational identify (Fiol & Huff, 1992)
12. An organizational member will attribute their satisfaction to the appropriateness of the underlying behavioral schema.	Self-discrepancy theory (Higgins, 1987)
13. An organizational member's satisfaction is partially determined by gaps, teleological, and dialectic in nature.	Systems theory and dialectic motors/theories of organization change (Morgan, 1986; Van de Ven & Poole, 1995)
14. Probability of change in organizational schema is a nonlinear function of satisfaction.	Aspiration-level theory (Kiesler & Sproull, 1977)
Agent interactions	
15. Organizational members' interactions induce flows of information and resources.	Machine models of organization change (Morgan, 1986)
16. Multiplier effects and sensitivity to perturbations depend on interconnectedness within the organizational system.	Population ecology theories of organization change (Hannan & Freeman, 1989)
17. Tags facilitate the formation of organizational subunits.	Organizational symbols (Schein, 1992)
18. The formation of organizational subunits increases performance due to decentralization, diversification, and specialization.	Population ecology theories of organization change (Hannan & Freeman, 1989)

and analytical capacities. The perceived organizational state is an amalgam of images, stories, thoughts, beliefs, and feelings.

The desired state is driven by and feedbacks to a "shared vision." The difference between the perceived organization state and the desired organizational state creates a "state gap." The state gap motivates or demotivates an individual's readiness for change. Miles and Snow (1978) demonstrate that an executive's perceptions of their organization's environments link causally to their decision making (Burke & Litwin, 1992). Saraph, Benson, and Schroeder (1989) demonstrate how organizational quality context is mapped into organizational response (as modified from Kiesler & Sproull, 1982) via a "gap" between desired and perceived states. If the gap is too big, change may be deemed impossible; if the gap is too small, change may be viewed as being unnecessary.

A change strategy then naturally follows: The first step must focus on developing a shared vision. This strategy has become an increasing focal point among many change strategists (e.g., Goldstein, 1994; Mintzberg, 1994; Schein, 1992; Stacey, 1992). Management needs to implement means by which vision can emerge from the group, and management's vision can gain acceptance among organizational members (Gioia & Chittipeddi, 1991). Other actions which help increase the state gap include co-location of cross-functional teams, team building, and various socialization strategies by top management (e.g., open door policy). Such sharing will also heighten the awareness of co-dependency among organizational members.

The second part of the change strategy is to alter the individual's perspective on the current organizational state. This amounts to increasing the amount and type of feedback available from the environment (e.g., customer surveys, using customers on design teams, etc.), improving individuals' communication and listening skills, improving the use of advanced information technologies which enhance transfer of learning (e.g., electronic mail, laboratory notebooks, virtual conferencing, etc.), and removal of (bureaucratic) decision-making hierarchies. Goldstein (1994) advocated the use of "difference questioning" to bring the system far-from-equilibrium and thus to a potential bifurcation. By highlighting differences rather than consensus one begins to surface the mental models being used by individuals (Argyris & Schon, 1978) and begin true dialogue (Senge, 1990).

A different school of thought, dialectic theory, posits that change is initiated when opposing events, forces, and values interact with one another. It is through the resolution of "thesis" and "antithesis" that change occurs. Dialectic theory, emanating from Marx's theory of social change, follows three principles: (a) the mutual interprenetration of opposites, (b) the negation of the negation, and (c) the transformation of quantity into quality (Morgan, 1986). The dialectic mode of organization analysis can be found, e.g., in the work of Heydebrand (1977).

Take as an example the implementation of TQM. TQM is steeped in a paradigm of control (Dooley *et al.*, 1995). Concepts like reduction of variation, defined and standardized processes, management by fact, causal thinking, etc. all stem from the "Newtonian" paradigm of control and equilibrium, as manifested in the principles and practices of scientific management. Yet, TQM also has a learning component to it. Employee involvement, empowerment, and cross-functional cooperation are an important part of TQM. TQM thus has both mechanistic (control) and organismic (adaptive learning) components (Anderson, Rungtusanatham, & Schroeder, 1994; Spencer, 1994). These learning components, in some ways, are in direct competition with the control components (Sitkin, Sutcliffe, & Schroeder, 1994).

For example, many companies attempt to standardize the manufacturing methods they are using across different production facilities. Typically, a central resource (pilot production facility) experiments to determine the optimal process methods. These are then standardized and other work groups are held accountable to following these methods. No sister plant is allowed to change methods unless it is authorized to do so by the central authority. This maximizes control, but it minimizes learning potential. Instead of having multiple plants all experimenting with different methods and learning, and sharing accumulated knowledge, there is only one experimental site. Conversely, decentralization of the process methods will tend to quicken reaction time and breed novelty in operations; failures will occur, however, and products from one facility may not be compatible with products from another because of quality inconsistency. As organizations struggle through such issues as centralized vs. decentralized control, control vs. learning, alliances vs. competition, etc., such dialectic conflicts may give rise to novel organizational solutions.

Design Principles for Complex Adaptive Organizations

A truly complex adaptive organization would appear best suited in semi-turbulent and turbulent environments where change is imminent and frequent. The art of designing such systems successfully is that convergent and divergent forces must be balanced, not in a linear, additive way, but in an organic fashion (Goldstein, 1994; Kelly, 1994). Here are some general guidelines: (a) create a shared purpose, (b) cultivate inquiry, learning, experimentation, and divergent thinking, (c) enhance external and internal interconnections via communication and technology, (d) instill rapid feedback loops for self-reference and self-control, (e) cultivate diversity, specialization, differentiation, and integration, (f) create shared values and principles of action, and (g) make explicit a few but essential structural and behavioral boundaries.

It would appear that one business organization has been developed, from scratch, using the principles of CAS. Hock (1995) portrays the design and evolution of VISA USA and VISA International. VISA was developed using five principles: (a) it must be equitably owned by all participants (the banks), (b) power and function must be distributive, (c) governance must be distributive, (d) it must be malleable but durable, and (e) it must embrace diversity and change. Its transactions exceed $650 billion annually, and yet runs with a core staff of 3000 distributed in 13 countries; its present communication system was developed in 90 days for less than $25,000. This success story indicates: (a) CAS theory can be used effectively to design a world-class business, and (b) designing such systems anew may be easier than changing existing organizational structure and practice.

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