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Toward a Theory of Leadership in Complex Systems: Computational Modeling Explorations

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Abstract: *I propose a new theory of leadership in complex systems based upon computational modeling approaches that have appeared to date. It is new in that it promises an approach that is well specified, coherent across levels of analysis, is transparent to the outside observer and can be modeled computationally. Although many of its independent components have been modeled, the underlying theory connecting these models is articulated here for the first time. Leadership is defined as those aspects of agent interactions which catalyze changes to the local rules defining other agents' interactions. There are five distinct aspects of leadership to be observed. Leadership involves actions among agents that: (a) identify or espouse a cooperation strategy or program, (b) catalyze conditions where other agents choose to participate in the program, (c) organize choices and actions in other agents to navigate complexity and avoid interaction catastrophe (sometimes called "complexity catastrophe"), (d) form a distinct output layer that expresses the system as a unity in its environment, and (e) translate feedback into structural changes in the influence network among agents. The contribution of this approach is discussed.*

Key Words: leadership, complexity theory, computational organization theory, computation modeling, complex systems

INTRODUCTION

Although computational modeling has become increasingly popular in many areas of social science, economics, ecology, and management, a recent survey (Hazy, 2007a) showed that there has been surprisingly little use of this method in leadership research. What has been done, however, is unique in the leadership field. It is broadly multi-disciplinary and includes contributions by researchers whose primary domains include mathematics, physics, economics and computer science as well as the traditional fields of psychology, sociology and management. This paper extrapolates the individual insights from these computational models of leadership and asks: If extant computational research is

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taken as a starting point, what can be said about the theory that underlies these models? Can they be tied together into an overarching theory of leadership in complex systems?

I will begin with a brief background description of the mathematical theory that underpins computational models of leadership. Next, the various definitions of leadership underlying the models are used to motivate a set of propositions that fill out a more complete picture of what leadership in complex systems might mean. Taken together, I believe these propositions constitute a research agenda for a new theory of leadership in complex systems, one that offers great promise for empirical research.

THE NATURE OF LEADERSHIP IN A COMPLEX SYSTEMS

Perhaps the reason that leadership has seen only limited computational modeling research is that until recently, the field has focused on individual and dyadic processes; in other words, leadership research has focused almost exclusively on improving the leader-follower relationship by understanding the competencies or behaviors of individuals as they influence one another in organizational settings. Related questions such as individual and collective cognition, interpretation of events, and nuanced communication, are not easily addressed using computer modeling. There has been some progress, however.

Early in the 1990s, game theory researchers built upon prior theory (Rapoport, 1967) to explore the mathematics underlying the coordination of strategies among players in multi-player, multi-trial games (Calvert, 1992). In exploring these game theoretic situations, emergent leader-follower dynamics became an area of focus. In a nod to sociobiology (Wilson, 1975), researchers looking at dyadic interactions labeled the first mover as “the leader” in a particular multi-player game (i.e., the “battle of the sexes” or “the leadership game”). This game is characterized as having an advantage for the player who commits to his or her move first (Calvert, 1992; Colomer, 1995; Rapoport, 1967) and thus limits the options available to the other player. The first mover agent is said to choose to act as “the leader,” in effect setting the rules for future interactions. This is the case for this game because each equilibrium state is unfair to one player or the other. Equal outcomes can only be achieved by alternating choices in each subsequent round such that parity is achieved, but only in the long run (Jones, 2000). These applications of game theory mathematics to leadership provide conceptual support for many of the computational models that followed.

Other researchers have combined the idea of games with dynamical systems analytics to examine the interpersonal dynamics at work in problem solving and task oriented teams (Guastello, Craven, Zygowicz, & Bock, 2005; Guastello & Guastello, 1998). In one study, researchers found a dynamical attractor pattern at work within the system of team interactions as the system moved toward the assignment of an individual as a leader in the group. Using nonlinear analytical techniques, the resulting team structure was shown to be predicted to a significant level by an analytical attractor called the “swallowtail”

(Guastello & Bond, 2007a; Guastello et al., 2005). These studies and others like them imply that there may be rich research prospects in the study of leadership when it is considered under a rigorously defined complex systems paradigm (Panzar, Hazy, McKelvey & Schwandt, 2007). Computational models, like those discussed in the present analysis, begin to offer such a framework. The remainder of this article draws on the computational and analytical studies to date (Hazy, 2007a; Hazy, Millhiser, & Solow, 2007) in an effort to move toward a theory of leadership in complex systems that is relevant to organizations operating in the knowledge age (Hazy, Goldstein, & Lichtenstein, 2007; Uhl-Bien, Marion, & McKelvey, 2007).

Leadership Espouses a Program of Action and Catalyzes Participation

The earliest computer simulation of leadership explored the underlying dynamics of the "first mover" advantage in the leader-follower relationship. In the context of nonlinear dynamical control theory, Hubler and Pines (1994) developed an agent-based model that generated results similar to those of the leadership game used in mathematical game theory. They found that when the first mover, or "leader" agent as they called it, was the first to make an active effort to shape the environment to its ends, the second agent often found it more efficient to synchronize its actions with the "leader" agent's approach rather than compete using its own strategy. This dyadic situation remained stable so long as a better alternative cooperation strategy was not espoused by the follower agent. If a better choice was espoused by the second agent, the new cooperating strategy might be adopted by both agents and the leader-follower state would flip, to what might be called the follower-leader state.

Phelps and Hubler (2006) extended this idea to multiple agents and explored the dynamics wherein individual agents choose to "join" a group that is pursuing a common strategy or program of action. In these models they found that after a time delay, a bifurcation point occurred—a relatively rapid change from a condition where agents acted in their own narrow self interest to one where the agents cooperated in a common purpose—when even a single agent had a reason to cooperate and where there was sufficient peer pressure to participate. Implicit in these studies are assumptions about two aspects of leadership among agents that begin to help researchers know when they are observing "leadership" among agents. In particular, these studies imply the definition.

Definition 1

"Leadership" is observed in a complex adaptive system when the actions or communications of one or more agents, called "leader agents," can be shown to espouse an approach or cooperation strategy for working towards a common objective, herein called a "program of action," such that choosing to participate in the program is an attractor for the individual choices of two or more agents.

A leader agent is said to influence other agents, called followers, when it offers a set of choices, tasks and resources—together constituting a program of action within the collective—that is adopted by the followers. When this occurs, the individual actions of the followers and the leader become inter correlated. They begin to act as a system. By adopting a program, each follower agent chooses among the programs espoused by potential leader agents. They make their choices with respect to which program to follow according to the relative reputations of the espousing agents. The choices are contingent on the specific situation and on the nature of the social influence, or peer pressure, that is present. For each agent making a choice, the reputation of each of the other agents with which it interacts is determined by its perception of its prior history with that agent as well as the expected future prospects for their relationship. Agent A's perception of the reputation of Agent B is thus the "weight" of Agent B's influence on the choices and behaviors of Agent A. Note that in this definition, reputation is not an attribute of Agent B. Rather, in this definition each other agent's reputation is a metric that is locally available within Agent A to describes the "weight" of that other agent's potential influence on Agent A's choices. Interactions among these influencing relationships are also possible. These interdependency dynamics at the agent level would be an interesting area for future research.

Along these lines, in addition to the attractiveness of a program itself, Phelps & Hubler's (2006) results assumed that the agents are influenced to adopt a common strategy because the social influence of other agents creates social pressure to conform. In other words, their model assumed a parameter that reflected the level of peer pressure weighing on individual choices. This observation leads to another definition.

Definition 2

Leadership is observed in a complex adaptive system when the actions or communications of one or more agents catalyze conditions such that at least one other agent chooses to participate in the program being espoused rather than continuing to act for its own account or according to an alternative program.

Further, agents that adopt a particular program of action are said to be recruited by leadership into that program. Thus, for any given program, there are agent that have been recruited and are caught up in the attractor (one could say that they are "turned on" to the program), and those that have not been recruited (and thus are "turned off" with respect to the program).

Although this article is primarily descriptive, an important normative consideration in any leadership theory relates to the constructive versus destructive ends of the program being implemented and the source and nature of the social influence that is created. This concern is sometimes described as the "dark side of leadership" (Conger, 1997). The dynamics described above and in the remainder of this article are agnostic as to the moral or ethical status of the programs of action that are espoused and to the leadership behaviors and communication strategies that are employed to achieve results. I will return to this issue in the concluding section where I offer some ideas about how future research might shed light on normative and proscriptive concerns.

Observing Leadership in Complex Systems

As described earlier, game theory (Calvert, 1992; Colomer, 1995) research and the agent-based models that followed (Hubler & Pines, 1994; Phelps & Hubler, 2006) implied that cooperative leader-follower relationships can form into a program of action that becomes an attractor for agent choices; in other words, the perceived benefits of cooperating outweigh the costs. As a result, agents choose to cooperate with one another. A program of action, like a multi-agent cooperation strategy in game theory, is an attractor if and only if, once agents try it, they tend to stick with it. The program attractor's "stickiness" can be described in terms of the "depth of the program's basin of attraction" in addition to its evenness (versus ruggedness). For the most part, when an attractor is deep and even, small deviations from the program—for example, a lapse in a single round of the game or choices at odds with the program—are forgiven and do not cause the agent to abandon the strategy or program of action all together. The specific shapes of the attractors vary as the relative fitness characterizing particular combinations of interacting choices and other situational differences are expressed as differing outcomes for the system and the agents involved. If the attractor is sticky enough with respect to a particular agent's choices, the agent tends to stick with the program even though circumstances vary and the particulars of the outcome for that agent may be difficult or impossible to calculate. The agent becomes stuck in a program of action, acting out its routines and taking the decisions that the program implies.

The diagram in Fig. 1 shows a collection of agents that are initially connected in a "small worlds" social network, a reasonable assumption given what we know about network theory (Watts, 1999). This network structure serves as a connectivity substrate for further interactions (Anghel, Toroczkai, Bassler, & Korniss, 2004; Barabasi, 2002). In the figure, the overall system is trending toward a series of disconnected program attractors, one within each cluster of strong ties (Phelps & Hubler, 2006). It is assumed that each of these groups is under the influence of a locally active leader agent who espouses a program of action for its own or for a perceived pro-social benefit. If the program is an attractor, other agents adopt the program of action. The leader's influence toward the program is show as arrows in the figure.

The story in each cluster in the figure might go something like this: Certain agents, first movers (Colomer 1995), do so by espousing a program in an effort to personally benefit from the environment. In a multi-agent (i.e., multi-individual) setting, the Hubler and Pines (1994) and Phelps and Hubler (2006) models imply that the first mover is more likely to be perceived as a leader agent at that point in time. As such, that agent's reputation is increased in the eyes of the others because it is exerting influence over them. However, this first program can be replaced as the current program if an alternative is espoused by another agent; the alternative has a deeper attractor basin; and the other agents choose to adopt the new program of action. Once adopted, the program tends to stick precisely because it is an attractor for agent choices. This aspect of leadership can be interpreted as a leader espousing a specific strategic vision or way forward within an organization (Bennis & Nanus, 1985; Conger & Kanungo, 1994; Kouzes & Posner, 1987). If a better alternative is espoused and then adopted, most observers would agree that leadership had happened.

The Pines and Hubler (1994) and Jacobson and House (2001) models implied that the attractiveness of a program—the depth of its attractor basin—influenced agent choices with respect to participation. In this sense, the program presents a choice that is similar to the Stag Hunt game in game theory. In this game agents must decide whether to cooperate and possibly bring back a stag or to hunt alone and certainly get a rabbit. The stag is a better payoff, but to win requires cooperation (Guastello & Bond, 2004).

In addition to a purely economic choice, other models showed that the specific approaches taken by leader agents to create a conforming environment of social influence also encourages participation in programs of action. The attractiveness of the program and the environment of social influence (both aspects of leadership) interact and together impact the level of recruitment and retention of follower agents to a program, and by implication, to a leadership regime. Phelps and Hubler (2006) developed a model to ascertain the conditions when a group of individual agents would adopt a program of action espoused by a single agent. They found that if there were benefits to cooperation for a single agent, and if there was social pressure to conform above a threshold level, then a phase shift resulted. In a very short time, the choices made by agents within the group shifted from being dominated by self-interested and uncorrelated action to cooperative and correlated interaction as the agents began working together toward the espoused program of action. Dal Forno and Merlone (2006) found that the specific behavior choices of the leader agent—for example choosing to act as a role model in certain ways, or the method used to assign rewards and recognition or to exercise coercion—related to that agent's success at recruiting others to its espoused program. Taken together, these ideas suggest a proposition.

Proposition 1

Leadership among locally interacting agents can be observed to have at least two interacting aspects: IF (a) an agent espouses a program of action that is an attractor for agent choices, and (b) agents (not necessarily the same ones) catalyze social pressure to conform above a threshold level, THEN a phase shift occurs from independent agent action, uncorrelated to the cooperation strategy, to correlated agent action according to a program of action, and this result implies that leadership was present. The phase shift is stable and the enacted program and the participating agents constitute a decision-making unit of correlated action.

Computer modeling of the charismatic leadership process explores the question of how agents are recruited to a cause (Jacobsen & House, 2001). Their model looks at how constituents adhere to a new vision or leadership style (versus an old vision or alternative leadership style) to organize their collective activities. Their models effectively "sort" agents into groups that adhere to the one program or the other to varying degrees. When the new program—an alternative way of doing things—gathers a sustainable constituency, an alternative decision-making unit operating within a new attractor basin is established. Depending upon their local situation, some agents may chose to switch programs and join these alternative units. However, other already participating agents may either accept of reject new recruits as they also must decide whether to cooperate with additional agents. In the context of a particular program of action espoused by a particular agent, individuals in a collective self-sort into groups that either identify with the program, are active followers of it, commit to it, or reject it (Davis, 2005). To the extent that a population that commits to a program is stable or growing, the collective continues to organize around the espoused program. Taken together, these ideas suggest a corollary.

Corollary 1

Agents will self sort into and out of programs or visions according to a calculus of benefit to cost to themselves including access to high reputation agents with whom they wish to cooperate. These sorting choices are gated with respect to new entrants desiring to join, on the one hand, and current participants allowing new entrants to join at a potential cost to them, on the other.

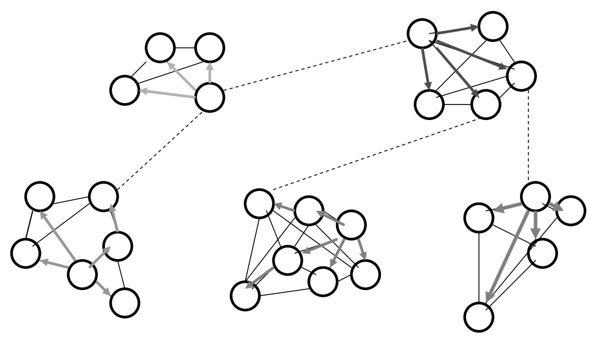

Fig. 1. Leadership influence operates on top of a network substrate with a small worlds topology; it generates new programs of action (shown as gray arrows) and through social influence catalyzes a phase shift to cooperative dynamics. Actions converge toward a program attractor, a cooperative strategy or model for success that is espoused by a first mover or the active agent with the highest reputation. Nodes can be individuals, decision making units or organizational capabilities.

Self-Similarity of Leadership Structures Across Scale

Assume that leadership influence develops on a small worlds social network among agents (Anghel et al., 2004; Barabasi, 2002; Granovetter, 1983) as shown in Fig. 1. Within a particular local group with strong ties, the tendency to organize into a program of action was described in Proposition 1. Once organized, action in these groups is inter-correlated and to a certain extent the agents tend to act as one entity. As a multi-agent—a collective of agents acting as an agent—this group of agents whose actions are correlated constitutes an organizational capability, a decision making unit in its own right that acts out routines and makes decisions as an organized group according to a program of action. It is worth noting that this definition of organizational capabilities is self-contained and consistent with the other definitions in this article; however, it is also conceptually similar to what has been described extensively in the literature of organizational capabilities (Dosi, Nelson, & Winter, 2000; Eisenhardt & Martin, 2000; Helfat, et al, 2006; Teece, Pisano, & Shuen, 1997). Exploring the similarities and differences between these definitions would be a useful area for further research.

As multi-agents, organizational capabilities can be organized by leadership as well. If benefits accrue to these multi-agents (and thus to their component agents as well) when they cooperate with other multi-agents and on a larger scale, a leader agent in one of the multi-agent groups can espouse an overarching program of action that includes specified actions across multiple organizational capabilities. This leadership influence might be exerted across weaker social ties in the small worlds network substrate. An overarching program like this would make sense for individual agents when the benefits of cooperation that are realized at the larger scale are perceived to provide additional benefits for them. Stated differently, adopting such a program makes sense where the larger scale program creates for the agents a dynamical system of interaction with a deeper attractor for agent choices, one that is more robust to perturbation than that of any of the other independently operating programs alone. The specific structures and the implications of their scaling features in a complexity science context would be an interesting area for future research. In any case, once adopted, such a program would strongly resist changes to agents' choices. According to Corollary 2, agents would be recruited and migrate to the larger scale program. Thus considering Proposition 1 at higher levels of scale suggests a proposition.

Proposition 2

Locally interacting groups of agents acting in concert according to a common program can act as capability multi-agents. Like agents, these multi-agents can organize according to an inter-capability program IF (a) an inter-group program is signaled by an agent across the inter-group-ties such that the larger scale program forms an attractor basin, vis-à-vis smaller scale programs among individual agents, and (b) the inter-group pressure to conform as enacted by a subset of agents is above a threshold level.

As agent interactions occur through time, heterogeneity develops naturally in the network that connects each agent to other agents or to resources, tasks, and knowledge, either by chance or as a result of heterogeneity among the agents themselves. Proposition 1 argues that relatively stable leader-follower relationships emerge naturally in human organizations. When one combines this with the realization that heterogeneity in influence among positions within the organizational network is inevitable, the potential for a concentration of influence in just a few agents, with respect to a large class of decisions across a large aggregate, becomes apparent.

An agent-based model simulated advice and influence among many agents in a multi-player, game theoretic setting (Anghel et al., 2004). The model showed that, in playing a particular game, the minority game, large collections of agents that began as connected in a small worlds social network—where groups of agents are connected locally in a dense network of strong ties while some of the agents are connected to many agents over weak ties (Barabasi 2001; Watts, 1999)—would self-organize into aggregates that were all influenced in their choices by a single agent. This simple result may eventually help explain the mechanisms underlying the concentration of leadership influence in a few agents on a larger and larger scale all the way up to the organization level. Furthermore, the study showed that, when one graphs the number of agents influenced by a given agent versus the number of agents who exhibit a given level of influence, the graph is scale free; that is, the numbers are related by a power law. If one assumes this relationship can be implied more broadly to a class of decisions, then a corollary to proposition 2 is indicated.

Corollary 2

A collective of multi-agents operating in concert according to a larger scale program of action can also form a multi-agent at this even larger scale, a multi-agent composed of other multi-agents. Self-similarity among these multi-agents across levels of hierarchy implies a scale free topology in the network of agents and further implies that preferential attachment is at work as all agents prefer to attach to others with the highest relative reputation.

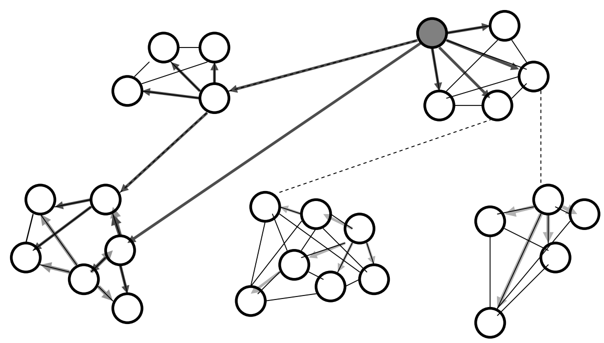

Fig. 2. Cooperating units form capabilities, multi-agents that cooperate through leadership influence and converge toward attractors. Agent to agent influence is based upon perceived “reputation” while competition to connect to the most centralized agents consolidates influence in “leader roles” shown in gray.

Leadership Navigates Complexity to Avoid Catastrophe

In the mid 1990s, computational organization science (Carley & Prietula, 1994) was developed as a theoretical formalism. It built upon Simon's (1976) notion of bounded rationality and provided an organization science context for agent-based modeling in organizational settings (Carley, 1992). When collections of agents perform specific tasks, those agents who find themselves overwhelmed by copious interactions at the center of the activity can exhibit behaviors that might be considered leadership (Carley & Ren, 2001). Further, differences in the particular interaction style of the agents occupying these positions can influence the evolution of the network structure and how well it performs and adapts (Schreiber & Carley, 2006). The early studies in computational organization theory only hinted at leadership; they did not explicitly include leadership in their theories. In the last few years, however, team and team leader simulations have appeared (Black, King, & Oliver, 2005; Black & Oliver, 2004; Dal Forno & Merlone, 2006; Schreiber & Carley, 2004; Schreiber & Carley, 2005; Solow & Szmerekovsky, 2006) to explore how agent interactions can be affected by differing leadership styles.

Implicit in these studies are assumptions about a third aspect of leadership among agents: leadership somehow navigates the complexity of interactions among agents. According to Corollary 2 above, due to preferential attachment dynamics in the connections among agents (Barabasi, 2002), some agents become more centralized in the network than others (have more connections). Due to Simon's (1976) bounded rationality assumptions, these highly centralized agents are subject to cognitive overload, a condition where the demands of the position far exceed the agent's ability to function successfully against all demands (Carley & Ren, 2001). To prevent cognitive overload at the agent level and a resulting complexity catastrophe (Kauffman, 1995) at the network level—a situation where too many interdependences among agents greatly reduce performance—the structure of the influence network must change when certain agents become too centralized. Following the terminology of Solow and Leenawong (2003), I call this the combined cognitive and network risk an "interaction catastrophe." Something must be done to mitigate the risk of interaction catastrophe in organizations; interactions with a subset of agents might be reduced as the work is partitioned into sub-teams effectively severing connections with outside agents, or some individuals may become specialized having the affect of absorbing interactions at one agent that might otherwise have been spread among many agents (Surie & Hazy, 2006). Thus another aspect of leadership can be defined as follows.

Definition 3

Leadership is observed in a complex adaptive system when the actions or communications of one or more agents catalyze choices and action in other agents to navigate complexity and overcome the limits to cognitive capacity in order to avoid an interaction catastrophe.

Leader role as a persistent structural artefact

When a collection of cooperating agents is assumed as a starting point, researchers (Carley & Ren, 2001; Schreiber & Carley, 2004, 2005) have explored the resulting heterogeneity of influence among the cooperating agents. Combining cognitively restricted agents with variations in the cognitive demands placed upon them by their relative position in the network, these researchers have proposed that agents who become centralized in the network experience higher cognitive demand than others; they are faced with many competing demands upon their time and their resources, much more than they can accommodate.

By virtue of their centralized positions, they must also have higher reputations relative to others in the eyes of many agents. However, due to their individual limitations on time and cognitive capacity, that is, their limited capacity to connect, these agents will begin to deny requests for connection from some lower reputation agents. This sets up a competitive market for connection among agents based upon perceived relative reputation. Because of their centrality, certain agents gain higher status by selecting only high reputation connections in a positively reinforcing feedback loop. As such, they use their increasing reputations to adopt coordinating rather than working roles. These positions are often perceived as leadership roles (Carley & Ren, 2001; Guastello, 2007; Guastello & Bond, 2007b). This insight leads to a proposition.

Proposition 3

The degree to which an agent is centralized in a network positively relates to (a) that agent's reputation in the eyes of others, and (b) due to cognitive and temporal limitations, the likelihood that it will shed some of its connections to other agents—actions that permanently change social structure. This competitive dynamic embeds certain positions as "leader roles."

Combining the persistency of leader roles, as described in proposition 3, with the scale-free nature of agent influence proposed in Corollary 2 suggests that large-scale structures that approximate hierarchy may emerge and be persistent through time; that is, the structures that emerge may survive the transience of individual agents. As circumstances change for individual agents, successor agents may inherit highly influential positions in the network and inherent the reputation or status associated with that position as perceived by other agents. These observations imply a corollary to proposition 3.

Corollary 3A

Positions in the network structure that are highly centralized and meet the definition of "leader roles" in Proposition 3 tend to (a) persist, and (b) impute to their agents a higher level of reputation and thus influence (i.e., they influence more agents' decisions) within an organization than do other positions.

Although these positions persist, the system is also dynamic and changing. Schreiber and Carley (2004, 2005, 2006) showed that, if the behavior of the agents placed in identical leader roles varies—e.g., between a participatory leadership style versus a directive leadership style (Likert & Araki, 1986)—the structure of the network and therefore, presumably, the nature of organizational outcomes will likewise vary. Thus, another corollary to Proposition 3 is indicated.

Corollary 3B

When an agent is in a "leader role," as defined in Proposition 3, the specific approach used by that agent to shed or redistribute tasks, resources, knowledge, and connections to other agents (e.g., a directive versus a participatory approach to redistribution) will differentially affect the structure of agent influence relationships and thus the outcomes of collective effort.

Leadership and 'Program of Action' Attractors

Once again, assuming existing groups of cooperating agents, as described in Proposition 1 and assuming persistent leader roles as described in Proposition 3, increased density of connections and thus complexity become a concern. As shown in Fig. 3, a consequence of competition for influence is that the density of interconnection within each group and across different groups increases, and as this happens the possibility that an interaction catastrophe will occur also increases. The problem of too many interactions must be navigated.

This situation has been modeled (Solow & Leenawong, 2003; Solow, Piderit, Burnetas, & Leenawong, 2005) to identify the impact of leadership on outcomes in complex environments. A key inference from these studies is that one of the functions of leadership is to decrease the counterproductive aspects of overload; that is, to defer the possibility of interaction catastrophe. When the collective is engaged in highly complex functioning (Schreiber & Carley 2006) a rugged rather than uniformly deep attractor basin can characterize the program of action; confusion and coordination difficulty can result.

Leadership navigates this complexity to mitigate the risk of interaction catastrophe. For example, leadership among agents might serve to put additional weight on individual contributions according to expertise (Solow et al., 2005). Endorsement by an agent of another agent's right to veto a decision, for example, would be a leadership event. By transferring reputation and thus influence to expert members, the first agent effectively reduces the number of opinions to consider (Jiang & Burton, 2002) and thus limits the potential for complexity catastrophe. These observations lead to the following proposition.

Proposition 4

At the group or team level, IF leadership activities can be observed to (a) limit the impact of an interaction catastrophe, or (b) by endorsement and transfer of reputation, put higher weight on the contribution of individuals with greater expertise, THEN the program of action attractor basin for agent choices is deeper and less rugged and the perceived benefit to cost ratio increases for each agent as choices are made regarding continuing to participate in the program.

Leadership and Organizational Learning

Computer modeling research might also inform our understanding about how organizations learn independently from agent learning and the role of leadership in this process. In particular, computational models may provide insight into how organizations of interconnected agents might exhibit the equivalent of neural network learning within the environment. Such an organization would be "trained" by its experience according to a learning algorithm. For example, models help us understand how various leadership approaches influence a team's context for learning, a construct that identifies a group's potential for learning as structural changes within the team's internal functioning and the parameters of leadership influence (Black & Oliver, 2004; Black, Oliver, Howell, & King, 2006). When it is assumed that the interactions within the team imply choices that converge toward a program of action that enhances learning, the leadership approach taken would be observed to influence the team's development and learning path. This leads to a corollary to proposition 4.

Corollary 4A

For a group of agents or multi-agents, the specific leadership approach taken by the agents, that is, how leadership affects the relative reputation of each agent in the eyes of the others and how this changes with experience, impacts on the influence structure of the group network in terms of how fast and accurately learning occurs.

As described earlier, using dynamic network analysis, Schreiber & Carley (2006) demonstrated that the specific style employed by the agent in a Proposition 3 leader role permanently changed the connectivity structure of the network. From this insight it is a short leap to posit that leadership activity among agents has the affect of changing the influence structure among agents. Presumably, it does this by changing the reputation relationships among the agents according to some learning algorithm.

The specific learning algorithm used by the organization determines the system's ability to learn what succeeds in the environment and what does not; it might adjust the reward and recognition structure, the status hierarchy, or even take coercive actions in the case of failure. They might publicize a metaphorical "public hanging" for example. Research into neural networks implies that the learning algorithm that is implemented will benefit the organization as long as it changes the activation weights among agents in a manner that is statistically correlated with their relative contributions to success in the environment (O'Reilly & Munakata, 2000). To the extent it can be shown that the learning algorithm reflects the organization's experience and that it incorporates feedback from the environment into its structure in a statistically significant way, back propagation learning becomes a possibility. This means that the organization may act as a feed-forward neural network with individuals or divisions acting as nodes or "neurons" in the network. As the network's outputs (or responses) are compared to those desired for a given set of inputs (or stimuli), the influence relationships among the agents in the organization—the synaptic activation "weights" in the neural network—are changed to reflect the level of success in the trial. The following proposition is implied.

Proposition 5

Corollary 4A implies that back propagation learning can occur in organizations if (a) outcomes from the collective are tested in the environment, (b) unambiguous feedback with respect to the nature of the trial and its level of success is observed in the environment, and (c) a learning algorithm adjusts reputation weights among agents according to their contribution to the success achieved in the environment.

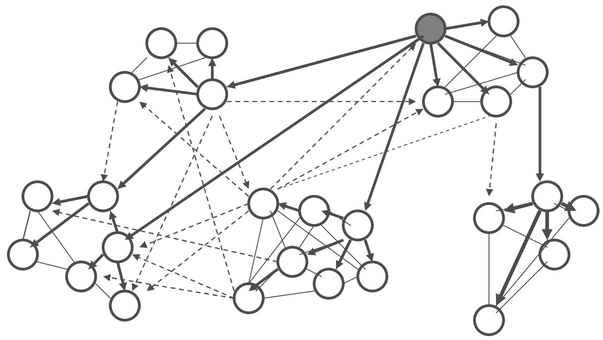

Fig. 3. Increased density carries risk of interaction catastrophe; leadership manages interaction risk with agents through partitioning. The system is challenged in decision making, control, structuring with respect to centralization versus decentralization, and unifying its identity to create "unity" in the environment.

Leadership Disambiguates Learning into Clarity of Action

Thus far in this paper, the agent collectives discussed have involved loosely connected teams and individual agents with no explicit hierarchy or division of labor. As has long been recognized (Simon 1962) these structures quickly becomes unwieldy in organizational settings. Proposition 3 and its corollaries imply that a hierarchy of influence may emerge and persist, and Proposition 4 and its corollary imply that the partitioning of interactions is also a likely result. It is thus reasonable to posit that these structural components also tend to persist and to interact with one another as loosely coupled specialized components or capabilities (Orton & Weick, 1990). This decomposition creates a situation where different components in the system adopt their own programs, each approaching its own attractor. The variations across programs may be in conflict, however, creating a situation that might be called “decompositional tension.” When the scalability of Proposition 2 is considered, the leader roles associated with the various loosely coupled components can also be organized by espoused programs of action and social influence (definitions 1 and 2). If this occurs, they can become catalysts that organize the overarching system into a hierarchy. On the first level, individual agents are organized into capability multi-agents. These are then organized into multi-agent capabilities, and then, perhaps, these multi-agent capabilities also become organized into even higher levels of aggregation. The leadership dynamics and other relationships among these various roles form an emergent and potentially persistent hierarchy. In order for the hierarchy to manage the decompositional tensions at work across the organization, it must somehow communicate with individual agents, each under the influence of local leaders. To maintain the system as a unity it must communicate to all of the agents through a signaling network of some kind (Hazy, 2007c). Although this hierarchy may be necessary to manage these tensions, is it also useful for the system in some way? Is hierarchy a necessary evil or a positive benefit? And what is the nature of the signaling network?

Two aspects of decompositional tension that must be managed are coordinated decision making and unified action. Hierarchy and signaling are needed for the organization to decide among the potential outcomes that are espoused by the various semi-autonomous programs that are in effect within the organization. As shown in Fig. 4, many agents are receiving input from the environment, and this input may be different or even contradictory. Research in neural networks implies that for learning to occur, a distinct output layer is needed to disambiguate among potential responses to inputs that compete for dominance within the network. This disambiguation corrects the limitations that are inherent in the localized learning behavior of disconnected, swarming agents in complex systems.

To address this potential for overwhelming confusion and inaction in such systems, I posit that the emergence of the leader roles of Proposition 3 enables the emergence of a feed forward neural network with back propagation learning through signaling that is implicitly embedded in the organization. As leader roles become disconnected from the input layer they form an output layer that speaks for the collective. Further, leader roles at the highest level of aggregation—the top management team—become the output layer in an organizational neural network that may, under the right circumstances, enable an effective back propagation learning process. The agents in this new top level output layer connect to the agents in leader roles at lower levels to form a hidden layer—middle management. In the neural network, the hidden layer serves to consolidate information from the other, input layer agents, and convert it into recommended programs of action—responses—to stimuli in the environment. The agents in the output layer choose among these programs. As they make these choices, they disambiguate the organization’s proposed responses to environmental stimuli and execute an unambiguous response in the environment. This leads to the definition of another aspect of leadership.

Definition 4

Leadership is observed when the actions or communications of one or more agents form a distinct output layer that expresses learning and action for the system as a unity in the environment; to do so the agents disambiguate learning and enable the unambiguous expression of action by the system in the environment.

Leadership uses feedback to change the influence structure among agents

According to Proposition 5, leadership by agents in the system, in particular agents in the output layer, must also process feedback from the environment into the organization as changes to reputation relationships and thus to the influence structure of the organization. This is done through a signaling network that is implemented through visible actions (Hazy, 2007b). Examples include promotions or firings, positive or negative recognition, changing reporting relationships, adjusting compensation or changing other status symbols in order to affect relative reputations among agents. This leads to the following definition.

Definition 5

Leadership is observed in a complex adaptive system when the actions or communications of one or more agents process information regarding success or failure in the environment and translate it into structural changes in the influence network among agents.

The nature of this learning, decision and disambiguation process has been explored computationally although its close relationship to back propagation learning in neural networks was not explicitly recognized prior to the present analysis. These models (Rivkin & Siggelkow, 2003; Siggelkow & Rivkin, 2005) looked at the complexity of decision making in a two division firm. It turns out that the outcomes of leadership decision making, even in this simple case, depend upon many interrelated factors. Specifically, the particulars of the approach taken to decompose decisions into departments, the patterns of interaction among departments, the level of activity up and down the hierarchy, information flows, agent abilities, and incentives were all seen to interact in complex ways, making the specific activities characterizing effective leadership highly contingent. This observation leads to the following proposition and corollaries.

Proposition 6

For an organizational complex adaptive system to learn and consistently adapt to its environment as a unity, unambiguous outputs must be tested in the environment by individual agents and information from the environment regarding success or failure must be propagated back into the organization’s influence structure based upon the success of the output and the nature of each agent’s contribution to it.

Corollary 6A

If there exists a small subset of highly connected, high reputation agents each expressing a distinct output for the system, the top of the hierarchy or the Top Management Team (TMT), and IF (a) there is a hidden layer of agents that are influenced (i.e., activated) according the relative weights of their reputations, (b) unambiguous outputs are tested in the environment and (c) feedback is processed by adjusting the reputation weights of agent pairs according to their participation in the output, THEN the system exhibits the properties of a multi-layer feed forward neural network with back propagation learning.

Corollary 6B

Each agent at the top of a hierarchy functions as the disambiguation layer for a particular output; it chooses among different adaptive responses within the hidden layer and disambiguates outputs to gather clear feedback about success in the environment.

Corollary 6C

Feedback about success in the environment is processed by adjusting perceived reputations among pairs of agents according to how they participated in the output. These are the synaptic weights that characterize the organization's neural network learning algorithm.

When the TMT interconnects into a tightly connected group with strong ties, it acts as an output layer for the system to disambiguate among locally determined adaptation strategies or programs, determine the system level output, and process the feedback by adjusting the reputation weights among agents. This is shown in Fig. 4.

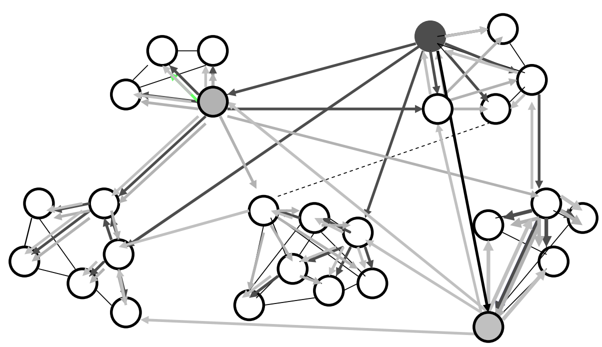

Fig. 4. Leadership enables collective intra-generational learning as reputation weights between agents change with experience; to address the limitations of a two-layer neural network, high reputation nodes (dark shading) form an output layer, the TMT, for disambiguation of output while other agents become a "hidden layer."

Table 1. A typology of Computer Models of Leadership

Researcher(s)	*Modeling technique*	*Theoretical basis*	*Key modeling results*
Micro leadership: The leader-follower relationship			
Calvert (1992)	Theoretical	Game theory	Explored the role of coordinated action in multiplayer, multi-round games
Hubler & Pines (1994)	Agent-based model	Nonlinear dynamical systems control theory	When two agents each attempt to predict and actively train the environment, a stable leader-follower situation emerges as optimal for each
Colomer (1995)	Theoretical	Game theory	Exploring the "leader game," a variation of the "battle of the sexes" game, demonstrates that acting first causes de-facto leader-follower behaviors to occur
Phelps & Hubler (2006)	Agent-based Model	Nonlinear dynamical systems control theory	With multiple agents, when the benefits of cooperation to a single agent interact with a peer pressure parameter, a state change occurs from self-interested agent behavior to cooperative behavior.
Meso-models of leadership: Individuals in collectives, groups and teams			
Carley & Ren (2001)	Agent-based modeling and networks	Computational organization theory	Examined the conditions within organizational networks whereby heterogeneous agent situations might enable leader-follower relationships to emerge
Jiang & Burton (2002)	Discrete event simulation	Contingency theory	The right match between leader expertise and team objectives positively affects outcomes

Table 1 (con't). A typology of Computer Models of Leadership

Researcher(s)	*Modeling technique*	*Theoretical basis*	*Key modeling results*
Meso-models of leadership: Individuals in collectives, groups and teams (con't)			
Solow, Leenawong (2003) Solow, Piderit, Burnetas, Leenawong (2005)	NK model	Mathematics and random network theory	Explored how leadership can improve performance and counteract interaction catastrophes in teams
Rivkin & Siggelkow (2003) Siggelkow & Rivkin (2005)	NK model and agent-based modeling	Top management teams and organizational design	The activity of a vertical hierarchy, how decisions are decomposed, incentives, abilities and communication flows—all influence potential performance of a top management team; what is best varies depending upon the needs of stability and the search
Schreiber & Carley (2004, 2005, 2006)	Agent-based modeling and dynamic network analysis	Computational organization theory	Found differences in team network configuration and performance outcomes when different leader style (directive versus participative) was used by the agent in the facilitator or leader-role
Black & Oliver (2004) Black, King & Oliver, (2005) Black, Oliver, Howell, & King (2006)	Agent-based model	Context-for-learning	Examined how leader agents with different leadership profiles affect the learning of groups; group level feedback to individual learning also examined
Anghel, Toroczkai, Bassler and Korniss (2004)	Agent-based modeling and networks	Game theory social network theory	Examined the emergence of scale-free advice networks that enable a small number of agents to influence the decision of many agents in the aggregate

Table 1 (con't). A typology of Computer Models of Leadership

Researcher(s)	*Modeling technique*	*Theoretical basis*	*Key modeling results*
Meso-models of leadership: Individuals in collectives, groups and teams (con't)			
Guastello, Craven, Zygowicz, & Bock (2005) Guastello & Bond (2007a, 2007b)	Lab experiment	Simulated game and nonlinear analysis	Found that team interactions tend towards a dynamical attractor which separated groups into primary leaders, secondary leaders and others.
Dal Forno & Merlone (2006)	Lab experiment & Agent - based Model	Team or groups	Demonstrated differential success of leadership styles due to sorting of followers among teams based upon different attitudes and behaviors of team leaders.
Macro-leadership: Organization level			
Jacobson & House (2001)	System dynamics	Charismatic leadership theory	Modeled followers identifying with, adopting, and committing to a vision, and then abandoning it as bureaucracy takes hold
Hazy (2004, 2006, 2007b, 2007c)	System dynamics	Complex systems, organizational capabilities and resource-based view.	Modeled the functional demands of a leadership process on a nonlinear dynamical social system; showed how leadership activities function to influence the adaptation of an organizational system in its exploitation and exploration of a changing environment
Davis (2005)	System dynamics	Routinization of charisma theory (Trice & Beyer, 1993)	Modeled five elements involved in the routinization of charisma

Leadership Catalyzes Changes to Local Rules of Interaction among Agents

Each of the above definitions, propositions and corollaries attempts to tackle the problem of leadership from a slightly different vantage point. The analytical and computational modeling studies that support them are summarized in Table 1. Taken together, leadership in a complex adaptive system of agents can be defined as follows.

Definition 6

Leadership is observed as those aspects of agent choices, actions or communications that catalyze changes in local rules of interaction among agents in the pursuit of a program of action that serves a purpose shared by at least two agents.

FUNCTIONAL DEMANDS OF LEADERSHIP IN COMPLEX SYSTEMS

The above analysis implies that leadership at the organization level is highly contingent and dependent upon learning and adaptation at lower levels in the system. Concerns with interaction catastrophe, the heterogeneity of networks, the decomposition of tasks, and the variations in hierarchy conspire to make identifying the differential impact of leadership activity at the system or organization level exceedingly difficult to parse. As shown in Fig. 5 the system must continually configure and reconfigure its multi-agent capabilities, and they must do so effectively as markets change. This challenge implies that there are several overarching functions of leadership, not only in the output layer or top management team (TMT), but distributed throughout the organization in what has been called a leadership meta-capability (Hazy, 2004, 2006, 2007b).

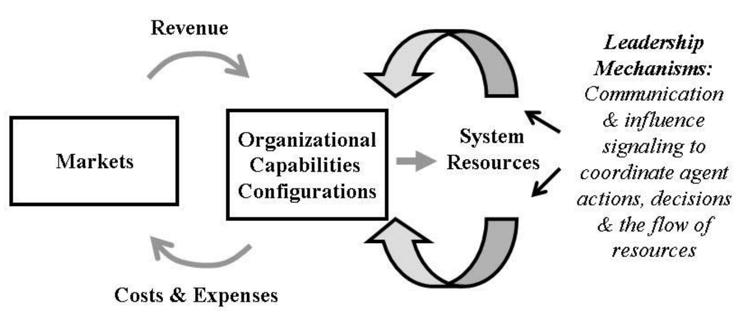

Fig. 5. Organizations as complex adaptive systems alter reputation weights to configure their capabilities, i.e. “learn” the environment; leadership mechanisms are embodied in the system in both bottom-up learning and top-down decision making and disambiguation.

The theory of leadership described thus far is helpful in moving inquiry beyond the apparently intractable complexity of human organizational systems.

This is because regardless of the complexity apparent locally within the organization, if systems learn through a back propagation learning algorithm as described, and if the top management team is considered to be the output layer in neural network learning, then our understanding of the functions of leadership is transformed. Definitions 4 and 5 imply that rather than simply setting direction or vision, the top management team (TMT) instead disambiguates learning across the system, executes "trials" in the environment, and then adjusts the influence structure within the organization based upon success or failure in the environment. Members of the TMT do this by increasing the reputation of those who were helpful to success and reducing the reputation, by repudiation or firing, for example, of those who promoted failed trials. Of course, TMT members also exercise leadership according to definitions 1, 2, 3 and 6, but the unique nature of the TMT is embodied in definitions 4 and 5 rather than the others. These two define the ways the TMT speaks for the organization. This theory of leadership is one where assigning and demanding accountability, the currency of many practitioner models of effective leadership, is explicitly specified as the definition 5 feedback aspect of leadership. In this way, by changing the reputations and influence of the agents that make up the organization, the system itself learns. But what does it learn?

Leadership and Organizational Purposes

To explore what the system is learning and how it is adapting through the actions of and relationships among its agents, it is instructive to go back to the first aspect of leadership that was described. Proposition 1 identified one dimension of leadership as "espousing a program of action" around which agents can organize. This visionary aspect of leadership has been studied in traditional models of leadership (Bass, 1985; Bennis & Nanus, 1985; Burns, 1978; Conger & Kunungo, 1994; House, 1977; Kouzes & Posner, 1987; Sashkin & Sashkin, 2003;) and has also been modeled computationally (Davis, 2005; Jacobsen & House, 2001). In addition, as organizational capabilities or groups of cooperating agents or multi-agents become established in interacting groups, there is a continuing need to organize individuals and capabilities. These dimensions of leadership have also been studied in traditional research where effective dyadic and group leadership behaviors have been explored (Bass, 1990; Likert & Araki, 1986; Yukl, 1998). These aspects of leadership are accomplished through the actions of agents as they espouse programs of action, initiate structure in the desired direction, and manage relationships (Avolio & Bass, 1995; Fiedler, 1967; Fleishman & Harris, 1962; Graen & Uhl-Bien, 1995) to coordinate effort among various agents, aggregates or multi-agents, and organizational capabilities. In other words, the various dimensions of leadership fit the pieces of the organization together into a whole.

To date, there is no theory of leadership that brings these disparate research streams together to articulate well defined integrative mechanisms across levels of analysis—from the individual, through groups and divisions, and ultimately to the organization itself—and how effective leadership at all of these levels relates to collective success in the environment. The approach described herein begins this process and thus represents a unique contribution to the field. Specifically, in the approach described herein, an overarching program of action predicts success in the environment for all parties invested in the overall effort. Based upon perceived success at achieving the desired result, the relative influence of agents within the organization is adjusted such that agents who contributed to success have greater influence in the future. In this way, all the aspects of leadership described in Definitions 1 through 6 are signaled to others across and throughout the organization along its influence signaling network (Hazy, 2007c). Agents on the top management team and elsewhere throughout the system catalyze changes to local rules of interaction based upon local knowledge and information from the environment such that the organization gains the means to sustain itself at the macro level. Individual agents, by participating in the system, can likewise sustain themselves and benefit from cooperative participation (Guastello & Bond, 2004).

As shown in Fig. 6, system dynamics modeling in general (Hazy, 2004) and also as applied to the microprocessor firm, Intel (Hazy, 2007b), has identified the key challenges for leadership when it is considered in this way. These models showed that to achieve success in the environment, the organizational system places functional demands on leadership in all five of its aspects (as described in Definitions 1 through 5) and at all level of the organization. How well these demands are met determines the ability of the system to adapt and survive in different environmental situations (Hazy, 2004, 2007b). The functional demands on leadership that were identified include: (a) Leadership generates new or novel programs of actions to organize agents and capabilities in ways that solve environmental challenges—and internal ones—and thus to foster sufficient variety in capabilities and programmatic options if they are needed; (b) once a program is selected by the agents involved, it catalyzes convergence in the action and choices among agents and multi-agents within a program attractor basin; and (c) it defines and maintains a sense of unity or collective identity (Sashkin & Sashkin, 2003; Schein, 1992)—that is, it defines the boundaries in which organizing occurs (Hazy, 2004) and the relative participation of the members. These observations imply a further proposition.

Proposition 7

Leadership in all of its aspects serves three functional demands in supporting the purposes of participating agents and groups of agents. *Generative leadership* identifies and generates variety in the programs of action, resources and capabilities available to the organization. *Convergent leadership* increases the perceived benefit to cost ratio of participating in a program of action; this deepens and makes less rugged the attractor basin associated with agents choosing to adopt a particular program of action. *Unifying leadership* promotes collective identity, or “unity,” and catalyzes actions and communications that pressure others to conform to a program; it clarifies boundaries and enables increased participation and cooperation at the margin within an attractor basin.

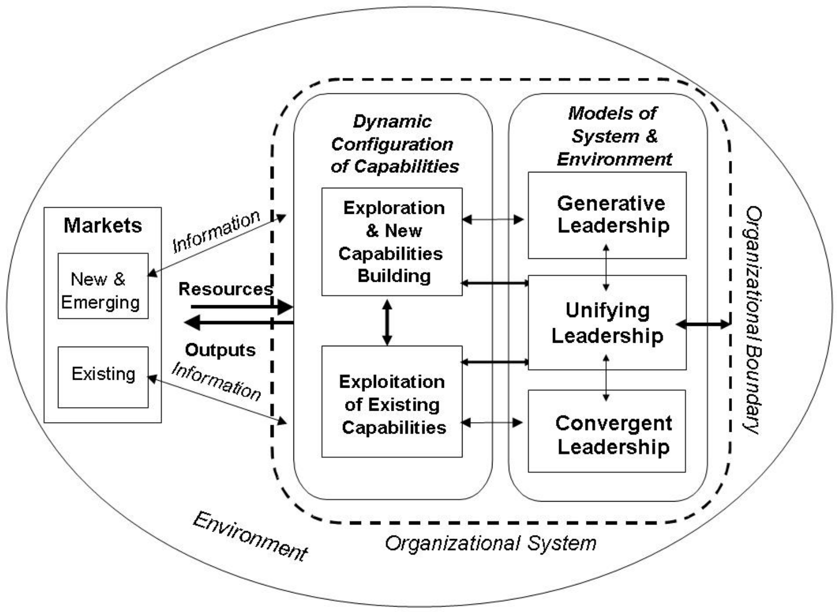

Fig. 6. To balance exploitation and exploration the system places three functional demands on the leadership mechanism: generating new capabilities and programs of action, unifying around those selected and converging action toward program attractors.

The above propositions and corollaries, and others that will inevitably follow provide the first sketches of a roadmap for a complex systems leadership research agenda.

DISCUSSION AND CONCLUSION

After perusing the early attempts to codify in software the very essence of something as ill defined as "leadership," it is unarguable that, although heroic in some sense, these first steps are nonetheless quite primitive. At the same time, in totality they show great promise for the development of a new theory of leadership in complex systems. Ironically, by stripping away the more subjective and nuanced aspects of the human experience—although admittedly these are the same parts that have the most visceral significance to us—and thus being forced by necessity to represent hopelessly complex human interactions in simple software programs, it becomes possible to see quite clearly pieces of the puzzle that might otherwise go unrecognized. Simple truths are often obscured by the very richness of individual human interpretation, filtered as it is by each person's unique experiences and one-of-a kind cognitive situation.

In this skeletal world a bare-bones narrative of leadership in organizations comes into focus: Each individual, each agent, seeks to perceive, predict, and where possible, control its environment—an environment that includes not only the physical elements, but also interactions with other agents, particularly ones in its social network that often exhibits a small worlds topology. As each agent seeks to control his or her environment, it disturbs what others—each on his or her own identical mission—are trying to understand. Hence, each agent faces a dilemma: do I accept the world another agent is creating (i.e., by following) or do I try to dominate those efforts for my own account (i.e., by leading)? When social pressure to conform is added, the equation becomes: Do the benefits of following, including the social benefits, outweigh the costs? Thus, when one agent is able to make sense of the many possibilities presented in the environment and to present a plan or program of action to enact it, other agents can relax their anxiety about controlling the environment and take another's enactment of events as their own. Under the right conditions, a cooperation attractor basin develops around the behavioral interactions within the program and organized activity follows.

As influence rolls up into larger aggregates, a new risk emerges: An interaction catastrophe might occur. On the team level, or on the level of teams of teams, modeling shows that too many interactions among group members can overwhelm agents and be counterproductive. Effective leadership mitigates this effect and reduces the negative consequences of interaction catastrophe by organizing interactions and information flows. This creates competition for access to high reputation agents and persistent leader roles that function as an output layer for intra generational neural network learning. The disambiguated output is tested in the environment and feedback is incorporated by changing agents' relative reputations and thus their influence in organizational interactions. This two layer network has only a limited capacity to learn. For complex learning, a third, hidden layer is needed.

The scalability of capabilities enables the emergence of hierarchy. When a true hierarchy evolves an executive layer, the TMT acts as the output layer while embedded leader roles, middle management, act as the hidden layer or layers. The TMT disambiguates the tensions among agents and groups, makes clear choices among several nuanced possibilities and tests the choices as "responses to stimuli" in the environment. Feedback with respect to the success of each response is back propagated into the system by a learning algorithm that changes the relative reputations of the agents involved in the trial. In so doing, the future weightings of the dyadic influence relationships between the agents (the "neurons") in the network better correlate with the desired response to the stimuli that are expected in the environment.

Turning now to the normative and proscriptive concerns alluded to earlier, one can ask how this theoretical framework can also provide normative insights that shed light on the dark side of leadership (Conger, 1997). In particular, one might ask if there are proscriptive lessons to be learned from this approach? One of the advantages of the complexity approach described herein is that it provides a dispassionate point of view from which an observer can make judgments. As such, one is better able to judge the ethical or moral nature of the programs of action being espoused and of the leadership methods being employed. An interesting area for future research would involve studies that seek to differentiate programs and methods as they are employed for ethical, versus unethical ends, as judged by the participants themselves or the institutional fields which typically have an interest in pro-social or ethical leadership. For example, of interest would be research that compared the leadership dynamics at work at the telecommunications company Worldcom in the 1990s, a period characterized by corrupt business practices at that company, with the leadership practices at Worldcom's primary competitor, AT&T, where no similar ethical lapses have been alleged during that same period. Were there discernable differences?

In conclusion, when all of the factors described here are included in an exceedingly complex nonlinear influence network, leadership writ large helps the participating agents by expressing the system's capabilities in the environment and learning from the results. Generative, convergent and unifying leadership are all necessary for a system of human agents to navigate a changing environment. When the system succeeds, presumably, the agents likewise succeed. Leadership is good for the system and it's good for the agents. Within the broad context described here, researchers can begin to fully understand the dynamics of leadership in complex systems at all levels, among agents at the working level, across dyads at all levels, in groups and even in the top management teams of today's large and complex global organizations.

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