Sociology: Computational Organization Theory

Kathleen Carley

Computational organization theory is a growing interdisciplinary area centered on the development of organization theory through the use of computational techniques. Research in this area grows out of work in many scientific areas including sociology, psychology, classic organization theory, and distributed artificial intelligence. The research in this area is united by a view of organizations as collections of processes and intelligent adaptive agents that are task oriented, socially situated, and technologically bound. This paper reviews this growing area and discusses both issues involved in the development of models in this area and theoretical issues that are being explored by work in this area. *Keywords:* simulation, organization theory, organizational learning, social networks, expert systems, computers.

Throughout the history of organization theory there has been an implicit goal of developing an understanding of organizations by looking at the situated action of the agents within them and the position of the organization itself in the larger environment. Weber (1922, 1968) sought to understand organizations through the causal relations that shaped the multidimensional phenomenon we refer to as the organization. His approach was a combination of the inspection of "ideal types" and historical analysis. His work and that of Taylor (1911), Fayol (1949), and others in scientific management shaped early work on organizations. Collectively, this early work suggested that a science of organizations could be built around models of the agents in the organization performing organizational tasks. These models could be idealizations of reality but detailed enough to lend insight into and to be tested against historical data. The task was critical, not just because of goal setting, but also because it affected issues such as requisite skills, timing, level of training, number of personnel, and so forth.

Cyert and March's *A Behavioral Theory of the Firm* (1963) arose

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out of this early work on organizations as collections of intelligent agents. Indeed, Cyert and March (1963) stands as a landmark for organizational theorists interested in formal models. Their work demonstrated the organizational impacts of bounded rationality and the value of process models for organization theory. Cyert and March characterize their research strategy using four points: (1) focus on a small number of economic decisions, (2) develop process-oriented models, (3) link models to empirical data, and (4) develop a theory with generality beyond a specific firm.

Another line of research, with roots that can also be traced to Weber's interest in external context, is on organizations as nodes in networks. The work of DiMaggio (1986) and DiMaggio and Powell (1983) on organizational fields and that by Burt (1992) on structural holes points to the importance of the inter- and intraorganizational networks in directing the organization's actions and the actions of individuals within these organizations. Collectively, these works and many others show the power of the network paradigm for describing organizations and markets. Computational tools for analyzing such networks are making it possible to blend this work with that on organizations as collections of intelligent agents into a unified formal framework.

Today these lines of research on organizations are merging in the area of computational organization theory. Computational organization theory is an interdisciplinary scientific area whose research members focus on developing and testing organizational theory using computational technology. The community shares a theoretical view of organizations as collections of processes and intelligent adaptive agents that are task oriented, socially situated, and technologically bound. Behavior within the organization is seen to affect and be affected by the organization's position in the external environment. The community also shares a methodological orientation toward the use of computational techniques (e.g., simulation, emulation, expert systems, computer-assisted numerical analysis) for developing and testing theory. Through computational models of organizations we can now begin to address formally the goals put forth by the pioneers of organizational theory.

Organizational theory was influenced early by the computational approach. Early computational organization theory was influenced by the cybernetics, general systems, and systems analysis movements (e.g., Ashby, 1956; Beer, 1964; Haberstroh, 1965; Chorafas, 1965); research on organizational formalism (e.g., Hage, 1965); interest in bounded rationality (Cyert & March, 1963); and process models of social behavior (Dutton & Starbuck, 1971; Abelson, 1968). Work by Forrester (1961, 1968) in system dynamics spawned an entire line of research (see, for example, Judson, 1993; Hanneman, 1988; Hanneman, Collins, & Mordit, 1992); as did Cohen, March, and Olsen's (1972) "Garbage Can Model," (see, for example, the work reported in March & Weissinger-Baylon, 1986).

Modeling Issues

Today there is no unified model or framework for characterizing organizations and on which work in computational organization theory rests. Rather, computational organization theory is currently dominated by research employing one of four distinct technological approaches: general organizational modeling, tool development, distributed artificial intelligence, and organizational engineering.

General Organizational Modeling

This approach is characterized by the development of models that are used to locate general principles and to explore general processes rather than to make specific predictions for specific firms. The models incorporate the use of ideal types and often abstract away from many of the complexities inherent in real organizations. These models often employ techniques such as numerical enumeration, matrix manipulation, logic, or Monte Carlo analysis. This area has its intellectual roots in sociology and traditional organization theory. Models are often developed to compare and contrast features of "ideal-type" organizations, networks of organizations, or agents. Illustrative models in this area include those by Cohen, March, and Olson (1972), Patrick (1974), Carley (1992), Glance and Huberman (1994a), and Harrison and Carrol (1991).

Tool Development

This approach is characterized by the development of computational and formal analysis tools. These tools include the development of m-agent logics, automated theorem provers, computational tools for locating properties of graphs (Krackhardt, 1994), and simulation frameworks for evaluating organizational measures (Lin, 1994b). The intellectual roots here vary widely and include graph theory, logic, and statistics.

Distributed Artificial Intelligence

This approach is characterized by the development of symbolic models that perform specific stylized tasks such as navigation or surveillance. A critical aspect of many of these models is the way in which the agent's knowledge and the shared knowledge is represented. Other critical components include the way in which this knowledge is searched and/or activated. Some research in distributed artificial intelligence employs general models of cognition that make very strong claims about the nature of agent intelligence (e.g., the work using Soar [Carley, Kjaer-Hansen, Prietula, & Newell, 1992]). This area has its intellectual roots in cognitive science and computer science. Models are often developed to address issues of communication, coordination, planning, or problem solving. Within some of these models agents are treated very generically, and there is an implicit assumption that the results are generalizable to networks of computers, networks of software programs, and networks of people. See Bond and Gasser (1988) and Gasser and Huhns (1989) for comprehensive reviews and illustrative papers.

Organizational Engineering
This approach is characterized by the development of highly detailed models often oriented to specific organizations and/or specific industries. The models are often immense and employ details at many levels. It is possible to use these models to develop both policy implications and sometimes to do what-if planning to help the specific organization with various design issues. Illustrative models include HI-TOP (Majchrzak & Gasser, 1991; 1992a; 1992b; Gasser & Majchrzak, 1992), ACTION (Gasser, Hulthage, Leverich, Lieb, & Majchrzak, 1993; Gasser & Majchrzak, 1994; Majchrzak & Finley, forthcoming), VDT (Levitt, Cohen, Kunz, Nass, Christiansen, & Jin, 1994; Jin & Levitt, 1994), and TIDES (Reuter, Perrin, Mitchell, Benett, & Grimes, 1994).

Modeling Challenges
Rarely today are organizational models as simple as the garbage can model (Cohen et al., 1972), which can be run in a few minutes on a small machine. Rather, many of the models require hours or even days to run a single test, and many must be run on high-performance workstations. Note, on models with multiple parameters many tests often need to be run with random parameter variations. This can result in weeks to months of data collection.

All researchers in this area face a number of modeling issues. Let us consider six of these—scalability, detail, data input, focus, micro-macro linkage, and data interpretation. Despite the increased sophistication of today's models, in many cases in order to make the models tractable it is still often necessary to create organizations composed of a small number of agents, for example, 2 to 13 agents. There is thus an issue of scalability. Do the results from these small organizations generalize to organizations with hundreds of employees? Second, in building computational models the researchers need to be careful about whether they are doing emulation or simulation. Emulation is much more exact and allows for predictions on a specific system but often requires much larger or "kitchen sink" models, whereas simulation is less exact, employs a higher level of abstraction, but may admit the discovery of general principles with relatively sparse models. In part, the tension here is between veridicality and generalizability. In part, the tension centers on the ability to make causal inference. In larger models (those toward the emulation end) the vast number of parameters may make it impossible to engage in complete response surface modeling and so to understand the specific cause of any particular result. However, in simpler models (those toward the simulation / numerical evaluation end) it is possible, sometimes, to completely evaluate all possible input parameters. The third issue refers to the increasingly onerous task of data input as we build larger models that rely on user input. In particular, in emulation models where we wish to characterize an existing firm, the development of simplified procedures for entering a description of that firm may be as difficult a task as building the emulation model itself.

The fourth issue is linking the micro to the macro. Within computational models, this issue takes a very specific form. Often researchers want to model organizations as collections of intelligent adaptive agents but to measure more macro output. Consequently, the computational theoretician must develop an answer to how the linkage is made: for example, are there processes of aggregations, what behavior emerges, and what is built in, and so forth. Often in developing a model, new issues of how the micro links to the macro emerge. The final issue is data interpretation. Today, with relatively large disk space, computational theoreticians' models can save vast quantities of results. This has created the need for postprocessors, smart agents, and internal graphical and statistical packages that can automatically parse the output and locate important results that might otherwise be overlooked.

Theoretical Issues

Within computational organization theory a wide range of theoretical issues have been addressed. Given that computational techniques make it possible to study dynamics (processes and results of change) and non-optimal conditions it is not surprising that many of the topics studied have these features. Among the issues examined are: organizational decision making, organizational culture, organizational learning, organizational design (communication and coordination), organizational dynamics, impact of new technology, and crisis management.

Organizational Decision Making

The study of organizational decision making has heretofore focused on case studies and formal mathematical models of teams. The latter work has typically focused on how to achieve optimal decisions (DeGroot, 1970), how to optimally allocate resources (Arrow & Radner, 1979), or how to reach consensus (DeGroot, 1974; Marschak, 1955). The case studies, however, demonstrate that within organizations, consensus is not necessary, is often unachievable, and is rarely the modus operandi for making decisions (March & Weissinger-Baylon, 1986). Further, these studies demonstrate that organizations rarely have the time, the access to information, or a static enough environment that it is possible to locate the optimal decision (March & Simon, 1958). Organizational decision making is thus portrayed as occurring in a messier and distributed environment. Computational organizational theorists build on these findings and examine the factors affecting organizational decision making in this messier environment where personnel come and go, there is a single decision maker or a team that need not reach consensus, and the decisions are often made through satisfying rather than because they are optimal (Arthur, 1991; Carley 1990, 1991, 1992; Cohen et al., 1972; Beroggi & Wallace, 1994; Davis & Smith, 1983; Masuch & LaPotin, 1989).

Organizational Culture
Organizational culture and, indeed, culture in general is increasingly receiving attention in the literature. Part of this work stems from a view that culture is key to understanding the formation and maintenance of groups and—within organizations—their productivity. A key computational piece in this area is by Harrison and Carrol (1991), who examine cultural differences and their long-term implications. Within computational organization theory more generally, culture is becoming more important as researchers find that cognitive, structural, and task-based constraints are not sufficient to explain organizational behavior. Rather, even with these factors specified there are still often multiple courses of action and multiple roles open to the agents in the organization. Culture, often in the form of setting individual agent "preferences" or "energy," comes into play as a critical determinant of action and role taking (Carley et al., 1992; Carley & Prietula, 1992; Cohen et al., 1972; Lin & Carley, forthcoming; Masuch & LaPotin, 1989). Such factors also play a role in what and how the organization learns (Lant & Mezias, 1992).

Organizational Learning
An area that is receiving increasing attention by computational organizational theorists is learning, along with the related phenomena of training, innovation, and diffusion. Among the issues examined are convergence (Lant & Mezias, 1992), entrepreneurship (Lant & Mezias, 1990), type of training (Alluisi, 1991); group action (Macy, 1990), cooperation (Carley, 1993; Carley & Prietula, 1994), diffusion and professionalism (Kaufer & Carley, 1993) and structure (Carley, 1992). This work varies in the type of learning model employed from classical learning theory models (Macy, 1990, 1991) to detailed artificial intelligence models (Tsuchiya, 1993; Masuch, 1990). For a more detailed review of this area see Lant (1994). This work suggests that individual learning and the organizational training procedures may be the basic building blocks for understanding how individual actions produce and reproduce group outcomes. It also demonstrates the criticality of feedback to organizational performance.

Organizational Design (Communication and Coordination)
By far, the issue that has received the most attention by computational organization theorists is organizational design. This work has a wide range and covers many design issues. Some of this work takes the general findings in contingency theory (Lawrence & Lorsch, 1967) and integrates them into a single expert system (Burton & Obel,

1984; Baligh, Burton & Obel, 1987, 1990, 1994). Other studies move beyond classical models of optimal allocation of resources and goods (Arrow & Radner, 1979; Gloves & Ledyard, 1977) and claims about structure (Galbraith, 1977; March & Simon, 1958; Staw, Sanderlands, & Dutton, 1981; Weber, 1922) to comparisons of allocation, communication, and command structures (Cohen et al., 1972; Carley, 1990, 1991; Carley & Lin, forthcoming; Masuch & LaPotin, 1989).

In all cases, the use of computational techniques have illustrated which of the arguments in the literature are internally consistent with each other. This body of research confirms that there is no one best organizational design; rather, organizational design is highly contingent. This work moves beyond this generic statement to a series of findings that specify how the various aspects of organizational design affect performance under specific conditions. Consequently, this research has refocused the interest of organizational theorists on the tradeoffs inherent in organizational design (Baligh et al., 1987) and neo-Weberian models (Hanneman et al., 1992). Commonly within the study of organizational design, organizations are modeled as networks of relations among subtasks, among people, between tasks and people (e.g., Cohen et al., 1972; Carley, 1992; Krackhardt, 1994; Lin, 1994a; Levitt et al., 1994). Also, it is common that these models take a systems (Haberstroh, 1965) or an ecological perspective (Kaufer & Carley, 1993).

Much of the computational work on organizational design focuses on issues of coordination and communication. This work has examined the impact of cooperation on performance and strategies for cooperating (Cammerata, McArthur & Steeb, 1983; Glance & Huberman, 1993), processes for achieving coordination when agents are distributed across multiple sights (Decker & Lesser, 1993; Durfee, 1988), planning (Corkill, 1979; Decker & Lesser, 1992), and general problem solving (Gasser & Toru, 1991; Davis & Smith, 1983). Models of coordination (Malone, 1987) and tests of their impact on performance (Lin, 1994b) have also appeared. Issues of current importance include the impact of organizational design and redesign on shared cognition, the development of individual mental models, and job distribution and redistribution in changing technological climates.

Organizational Dynamics

Organizational dynamics is an area of current interest. The term refers to the study of the processes and impacts of shifts in organizational designs and the evolution and alteration of organizations. Shifts in organizational design may occur through a variety of ways including evolutionary processes (Crowston, 1994), conscious reengineering (Baligh et al., 1987; Gasser et al., 1993), reactionary processes in response to the environment such as when crises occur (Carley, 1991), internal dynamics (Hanneman et al., 1992; Hanneman, 1988), and learning processes (Lant & Mezias, 1990). Computational models are particularly suited for the study of organizational dynamics because they let the researcher focus on the dynamics by which organizations are designed and redesigned (Cohen, 1986) and the impact of process on specific tasks (see for example Crecine's 1969 work on budgeting). This work brings to the fore a concern with how organizational performance can be assessed when organizations are continually being designed and redesigned or are evolving or naturally changing.

Impact of New Technology

Some of the current computational models admit the possibility of studying the impact of new technologies, particularly information technologies. This line of research follows from a long-standing concern on the part of organizational theorists with technology and communication (Thompson, 1962; Galbraith, 1977) and transform it into models of information systems and technology within organizations (Bonini, 1963; Mezias & Glynn, forthcoming). Such models can be used to do a what-if analysis and so explore what happens if the technology breaks (Carley, 1991) or is altered (Levitt et al., 1994) or a new technology is introduced (Majchrzak & Finley, forthcoming). Using such "what-if" studies, pre-intervention analyses can be done that have the potential to affect policy.

Crisis Management

Finally, computational organization theorists have approached the area of organizations and crisis. Classic studies on crisis have taken a case study (Shrivastave, 1987; Rogers et al., 1986) or comparative approach (Perrow, 1984; Staw et al., 1981). The crisis area is particularly amenable to the computational approach because it is difficult to collect data, and experiments are often either unethical or suspect. Thus, computational models can be used to go beyond the data and do forecasting and what-if analyses that admit multiple factors to be considered (Carley, 1991; Lin, 1994a).

Conclusion

The field of computational organization theory is growing rapidly. In the past 6 years a cursory analysis reveals at least 40 related publications per year as opposed to the half dozen or so per year prior to this. These publications, however, are spread out over at least 25 journals, proceedings from three different conferences, and books. In the past 3 years, more than six workshops in this area have been held in conjunction with the AAAI meetings and the ORSA/TIMS. The growing general interest in sociology with computational approaches (Bainbridge, 1987, 1990; Bainbridge, Brent, Carley, Heise, Macy, Markovsky, & Skvoretz, 1994; Brent, forthcoming; Wolfe, 1991) is reflected in this growing interest in computational organization theory. Finally, within the organization area there appears to be not only growing interest but an increase in the extent to which later work builds on earlier work and an increase in the sophistication of the models.

Across the field of computational organization theory there are common emphases. First, many computational theoreticians employ network representations for capturing the organization's design. Thus networks are used for linking subtasks to subtasks, subtasks to people, people to people, people to organizations, and organizations to organizations. The use of social network techniques for characterizing and analyzing these configurations is on the horizon. Second, there is an emphasis on process. Organizations are not viewed as static. Processes are seen as more important in establishing agent, task, and organizational boundaries than general traits. And finally, there is an emphasis on change. Computational techniques make it feasible to examine organizations in flux and to scrutinize minutely the processes by which individuals and organizations learn, adapt, react, and evolve.

Computational organization theory has the potential to change traditional views of organizations. The emphasis on process, task, and change may lead to a more dynamic yet situated view of organizations. The use of sophisticated models of cognition for modeling agents in organizations may give rise to a neo-information-processing paradigm. This should in turn improve our understanding of agency and action. The attention to organizations as collections of intelligent agents may lead to a better understanding of the processes whereby groups are formed and reformed. Finally, as the models become increasingly sophisticated, issues of informal networks, role, culture, demography, and power begin to appear in these models. As a result, these more comprehensive models may enable us to gain a better understanding of the full ramifications of social and technological changes within the workplace.

Many types of organizational problems are suited to the computational approach. One would use this approach to address issues of suboptimality, to analyze complex multidimensional problems, to examine the impact of critical or lethal events (e.g., crisis analysis), to address the impact of change in the short run, and to address issues of change. Not all issues warrant a computational approach. Finally, the computational approach can provide a practical benefit. With these models, it is often possible to engage in what-if analyses. To the extent that the models are verified and generalizable to the situation at hand they can provide a mechanism for exploring the ramifications of various policies.

The use of computational techniques is not an all-or-none proposition. Computational techniques can be employed fruitfully in conjunction with noncomputational models, human experiments, and empirical data to provide a more rich understanding of organizational behavior. For example, Glance and Huberman (1994b) use simulation to confirm analytic predictions and illustrate atypical behavior. Beroggi and Wallace (1994) combine computational and noncomputational analytic techniques. Heise (1978, 1979, 1987) employs a combination of computational models and empirical data to predict individual action. Burton and Obel have been at the vanguard in linking simulation and experimentation (1984). Baligh et al. (1994) could not have developed the Organizational Consultant without extensive analysis of real organizations and testing of their expert system using specific case studies. In the future, one should expect to see an increasing use of simulation experiments to fine tune and help define critical human experiments and field studies. One should also expect to see an increase in the use of simulation-aided data analysis. What all this suggests is that use of computational and formal techniques are becoming more accepted, and indeed sometimes indispensable, for organizational research and theory building.

Note

Kathleen M. Carley is associate professor of sociology and information and decision systems at Carnegie Mellon University. Her research interests focus on the joint cognitive and structural basis for social and organizational behavior in dynamic settings. Research areas include: (1) examining the impact of organizational design and agent skills on organizational performance and teamwork particularly under crisis conditions; (2) examining the interplay of social structure, cognition, and technology in affecting information diffusion and group formation; (3) encoding mental models from texts. She can be reached at the department of social and decision sciences, Carnegie Mellon University, Pittsburgh, PA 15213; 412-268-3225; FAX 412-268-6938; E-mail KATHLEEN.CARLEY@CS.CMU.EDU.

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