Computation and Social Systems

Report of the NSF ITO Grantees' Workshop
April 19-20, 1997

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DEPARTMENT OF COMPUTER SCIENCE

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I. Introduction

This report outlines issues, progress, and directions for future research in the field of Computation and Social Systems (CSS). It presents ideas and issues that emerged from a National Science Foundation (NSF) sponsored workshop held April 19 and 20, 1997, in Arlington, Virginia. The workshop brought together 52 principal investigators (or their co-investigators) representing almost all research projects currently sponsored by the NSF's Information Technology and Organizations (ITO) program. The purpose of this workshop was to provide an effective forum for members of this scientific community to meet, mix, learn about others' contributions, and articulate the significant research issues facing the community today and in the future. This event represented the first of such forums in recent years. This report captures ideas, issues, and conclusions that emerged from the workshop as understood and interpreted by the six person workshop steering committee. Further workshop information is available on the workshop web page at:

http://www.cs.colorado.edu/~skip/workshop/css.html

II. Background

> "Computing is inextricably and ubiquitously woven into the fabric of modern life...computing is a truly enabling and central technology"
> from *Computing the Future*, National Academy of Sciences Report [1].

As this introductory quotation suggests, it is the ubiquitous and enabling features of computing that make the technology so central to modern social systems, and it is the way that computing is inextricably woven into modern social systems, that is the primary rationale for research that examines the intersection of computation and social systems.

This field of research is not new. It began in the 1950s and 1960s with early theoretical and experimental work. Scientific work of decades past on theories of coordination, on computer support for collaboration, on artificial agents and distributed intelligence, and on computational theories of organizations, have all contributed to the birth of this area field. An initial, and continuing emphasis has been on social impact of computer and communication systems in groups, organizations, and society. Membership in this community of researchers has grown steadily as the researchers have broadened their scope.

Support for social impacts research within NSF began with Peter Lycos from the University of Chicago, who articulated the Computers and Society Program in response to concerns about issues of privacy and confidentiality, employment and unemployment and quality of work life related to the introduction and use of computers. Fred Weingarten and later Larry Rosenberg responded to the scientific community's broadening interest in the field, and the social impacts area was extended to include study of the economics of information, the economic and social impact of the information industries, and the impacts of information technology policy. New areas were also introduced in recent years in response to opportunities and challenges presented by new technologies and their uses. These areas include computer supported cooperative work, computational organization theory, digital libraries, and distributed intelligence and multi-agent systems.

As the early pioneers grappled with research on the complex questions regarding the interactions of computing and social systems, they realized that the problems being investigated required the contributions of researchers in disciplines outside traditional computer science. Consequently, the research community created multidisciplinary and interdisciplinary teams for research such as the social impacts of computing in large scale systems, computer supported cooperative work, digital libraries, and other test-bed research. Such research was viewed, and continues to be viewed, as complementary to independent research by individual investigators in the field.

As the 21st Century approaches, we are already in a world of ubiquitous computing and computing-enabled change which creates new opportunities for positive impact on groups, organizations and communities within modern society, on U.S. industrial strength in the information industries, and the nation's defense. This new world raises new issues and new opportunities which can be addressed within the evolving scope of research on computation and social systems, and on which progress can be fostered by widening the general awareness of these research needs, and by strengthening its institutional base.

III. Dimensions of Computation and Social Systems Research

Research in the field of Computation and Social Systems (CSS) is concerned with fundamental issues of computer and information science. It studies phenomena of information processing as accomplished by human, artificial, and a mix of human and artificial agents. Such information processing phenomena are found at all levels of analysis from individual agents to groups to organizations to communities to societies. One distinguishing characteristic of the CSS field is a focus on mutual interactions between computation and social systems, and the implications of these interactions for building future information systems and for "engineering" the future social impacts and sustainable use of information technologies *in situ.*

Computing has become ubiquitous, and digitalization is becoming ubiquitous. Modern society is now moving into a stage where there is real collaboration and interaction in problem solving activities between people and computers. We need to understand this evolution and leverage this potentially productive partnership. Though the particular nature of future information infrastructures and technologies is uncertain [2], one assumption is widely accepted: in the future, there will be more and more - not less - interaction between technology and people in social systems, and among computer systems themselves. These developments enable qualitatively different interactions, syntheses, and social forms, which will have huge and largely unknown impacts within society. It is important therefore to develop better understanding of varied aspects including: the technological possibilities, the technology-relevant aspects of social systems, the effective design of computer-enabled systems, the interaction of computational and social systems, the impacts of these systems, the effective engineering of future social impacts, and the sustainable use of this technology in social settings of all kinds.

This research is critical as the information industries become ever more central to national and international interests. Thirty years of study have shown that when the interaction of computation and social systems is not taken into account, the results are dismal. They can be seen in the large number of failures in systems building, the time and cost overruns, the computer systems that are built but seldom used, and the disruption to major parts of modern society when computerized networks are overloaded or damaged. On the other hand, thirty years of successful systems performing tasks previously not possible have also shown the tremendous potential that results when computing and the new capabilities it makes possible are effectively merged with social systems to created new systems, new organizations and an integrated synthesis of the two. CSS researchers have successfully integrated these in the past and represent a valuable resource to be tapped for the future.

In order to advance the research agenda outlined below, significantly more funding and visibility is needed for CSS research. Funding should be devoted to the areas identified below, as well as new areas that will emerge to be important but which cannot now be foreseen. There is little reasonable alternative.

IV. The Community of CSS Researchers

The CSS community is established and growing, but its breadth and depth are seldom appreciated. The community consists of researchers from traditional computer science, information systems, and from the emerging models of computing, and it also includes researchers from organization science, coordination science, economics, sociology and the social sciences broadly. The 52 participants in the ITO Workshop were representative of these disciplines.

Although diverse and distributed, the community of CSS researchers exhibits remarkable cohesiveness. This cohesion is being strengthened and institutionalized by the recent emergence of a number of broad-based "Schools" promoting integrated approaches to teaching and research on information, computation, and social systems in leading universities in the U.S. and abroad. These new schools variously focus on "information management and systems", "information and communication", or "informatics", but their central concern is the mutual interaction between computing and social systems. These new schools promise further growth of the community and greater focus of attention on information processing within leading universities across the nation. All of the new schools have a strong disciplinary base in the computer and information sciences while bringing in other disciplines concerned with social systems.

The following universities have established or are in the process of establishing focused schools related to CSS:

School of Information and Communication, University of Arizona (est. 1998)

School of Information Management and Systems, University of California, Berkeley (1996)

School of Informatics, University of California, Irvine (est. 1997)

School of Information Sciences, Indiana University (est. 1998)

School of Information, University of Michigan (1996)

School of Information Science, University of Pittsburgh (1997)

School of Information Studies, Syracuse University (1974)

The CSS community believes that individually and collectively, it is important to keep strong ties to existing core disciplines that make up the field while also developing new interdisciplinary knowledge, methods and tools. Thus, members regularly present at key conferences and publish in existing first rate journals, while also developing linkages with one another. As a first-rate example, community members publish in their own discipline as well as in Communications of the ACM and the ACM Transactions on Information Systems. When appropriate, members have also participated in and established specialized conferences or workshops and journals such as the annual CSCW conferences and the Journal of Computational and Mathematical Organization Theory.

V. Field Overview and Scope

The Computation and Social Systems field is wide in scope and requires multidisciplinary investigation. Its scope includes coordination theory, collaboration technology, the impacts of computing, multi-agent systems, computational organization theory, and other areas. The primary concern of the CSS research community is (1) to develop understanding of the role and use of computer and communication systems in groups, organizations, and society; (2) complimentarily, to develop understanding of groups, organizations, and societies from a computational and information-processing perspective, and (3) to bring these bases of knowledge and practice together in a productive synthesis for both understanding and managing CSS-related phenomena.

The field rests on the fundamental premise that the design of any technology requires understanding of the social contexts of its use, and that optimal use and sustainable integration of technology requires understanding of how technology enables new ways of working, organizing, and living. CSS research is concerned with developing scientific principles that can guide the effective design, construction, and social integration of information processing systems to support these new opportunities. The CSS community has identified five areas of particular importance in the near-term future, recognizing that these areas themselves will change over time. These areas are briefly described in the next section.

VI. Sub-Areas of Research

6.1. Coordination Theory

Theoretical research in CSS develops models of organizations and social systems, supporting analysis, prediction, and design of social structures taking into account the participants' information, communication possibilities, objectives, relationships, and incentive mechanisms. In constructing such theories, the area draws on concepts from diverse disciplines, including economics, management science, and computer science. Although work fitting within this category goes under many names (including organization theory, mechanism design, and others), we use the label "coordination theory" here to encompass the broad range of theoretical work bearing on the relation of information technology and multi-participant systems.

Information technologies can exert enormous influence on social systems, by driving the factors underlying their interactions. For instance, the information available to participants, costs and modes of communication, and implementation of incentive mechanisms all affect the types and outcomes of technology-mediated interactions. Theoretical models provide a means to evaluate the effects of alternate designs, and a guide to shaping both the technology and the social systems to produce more beneficial outcomes. This contribution may be realized for any of the various levels of study: broad social impact, collaboration within work groups, or behavior of human or computational agents within multi-agent systems. Although each of these levels requires models specific to its own context (and workers in these areas devote much effort to developing such models), there is also a need for fundamental principles cutting across the range of configurations. Such underpinnings help in evaluating the scope of a particular study's results, and facilitate the transfer of insights from one domain to another.

Past theoretical developments have produced a rich set of analytical tools for conducting these investigations. For example, studies in mechanism design have produced measures of communication complexity, and protocols that effectively allocate resources for a broad and precisely defined range of situations. Recent exercises in telecommunications policy (e.g., the FCC spectrum auction) and automation of deregulated markets (e.g., electric power transmission) have established the relevance of mechanism design to important national problems. In particular, the automated electricity market is an instance of a distributed mediation mechanism, where careful design of protocols, and explicit control of information dissemination is critical to fair and effective operation.

Other work of a very different nature, but still within the area, aims to catalog the space of organizational designs, and characterize the properties of alternate organization processes. For example, one research group has been compiling a "process handbook", with descriptions of processes expressed in quasi-computational terms. The formal specification tools associated with these descriptions facilitate implementing and reasoning about the processes, and promotes precise communication about organization processes among research groups.

As argued throughout this report, the pervasiveness of information technology in organizations and throughout society far outstrips our understanding of its effects and our ability to engineer effective multi-participant systems. The explosion in new media for augmenting interactions among human and computational agents will only accelerate this trend. Our economy devotes a great deal of resources toward designing and developing multi-participant information systems, and so there is a significant opportunity to leverage any improvements in the state of the art and practice. Reliable improvements will come only through development of sound design principles and powerful evaluation methods, enabled by robust and relevant theory.

6.2. Collaboration Technology

Collaboration Technology, closely linked to the field known as "Computer Supported Cooperative Work" (CSCW), defines a research area that studies the architectures and uses of computer and communication technologies to support groups, organizations, and communities. Associated with this area are questions of "How do people interact and collaborate?" and "How can technology facilitate and enhance this interaction and collaboration?" This emerging new focus of technology presents opportunities for new paradigms, new types of systems, and new ways of working. Along with these come new problems and new intellectual issues. Research methodologies utilized within this area include field studies, systems prototyping, experiments, simulation, and conceptual modeling. The techniques, technologies, and findings of this area have proven useful to enhance interactions ranging from real time face-to-face meetings, to asynchronous organizational workflows.

In fact, the area is striving to obtain more needed knowledge concerning technological structures, organizational structures, and social structures, in order to be able to produce successful technology enhanced group systems. Some of this knowledge is being obtained by observing non-computerized collaborative environments, and studying the ways in which people communicate, coordinate, and collaborate. For example, a recent article in the CSCW Journal reported on a detailed field study of workers in a control room in the London Underground railway system. This setting provides a clear example of cooperative work under time-critical conditions where much of the coordination is done informally. Coordination happens via over-hearing, "seeing out of the corner of the eye," and in other incidental ways. It turns out that this incidental coordination is effective and common-place, but our collaboration technologies are poor at supporting this, and sometimes destroy the possibility of incidental coordination. The above study led to useful, concrete design suggestions for Context Automation in this particular collaborative environment.

Much of the work within the collaboration technology area is applied research to gain understanding of collaboration issues via studies, like the London Underground; and/or via systems prototyping and participatory systems design and testing. Technologies such as real-time multi-user document editors and workflow systems are surprisingly complex and difficult to successfully engineer. In the systems architecture arena, many of the traditional approaches and concepts need to be re-thought, and re-invented. For example, locking systems, resource sharing principles, notions of transparency, and issues of information security and access, among many others, have been revisited, noting that the traditional approaches are frequently inadequate for collaboration technology. To ease the great difficulty of building experimental systems, research on collaboration toolkits and groupware development tools and environments is needed.

Research in this area is now regularly reported in CSCW conferences and journals. Commercial companies working in this area now promote many products labeled as "groupware." Commercial developments, coupled with recent visible successes and growth of prototype scientific and industrial "collaboratories" indicate the interest and promise of this direction. But the currently-limited capabilities, lack of clear principles, and dearth of broad implementation successes reveal the pressing need for additional research in this area. A further need is for the clear integration of the emerging base of theories and mechanisms of interaction, coordination, and collaboration, with new collaboration technologies under development; this integration has not progressed rapidly enough, and is a high-impact area of endeavor.

6.3. Social Integration, Impacts, and Sustainable Use

Over thirty years of CSS research, much funded by the ITO program at NSF, has shown how difficult it is to reliably build valuable computer systems for groups and organizations without a deep understanding of how the technical systems should be and are matched to the people they are meant to serve. Indeed, from the point of view of group or organizational effectiveness, the information processing system is a hybrid system in which people, as individuals and collectives, communication technologies, and computers are inextricably bound. To make successful information processing systems, therefore, inherently means understanding the interaction between computers and human social systems as much as it does understanding software architectures, data networks, or the numerous other components of a modern software system.

We believe that understanding the interaction of social and technical systems goes beyond engineering successful information system, however. Computers are almost universal in firms and other economic institutions. Moreover, they are diffusing rapidly and widely in public life as well, in homes, schools, political parties, and entertainment establishments. This widespread use of computing is likely to have both intended and unintended social consequences, and as a society we must understand these consequences to assess the health of the nation and to plan for the future.

From its earliest days the ITO program at NSF and its predecessor organizations have supported research on the fit of computing technology to groups, organizations and society, both to build better information processing systems and to understand their social implications. This research has proved useful in at least three ways:

(1) It has led to the development of new types of computer technologies that are better fitted to the tasks that groups & organizations perform. The computer supported cooperative work technology, described briefly above and represented in applications like Lotus Notes or group decision support systems, have been heavily influenced by research in this area.

(2) It has led to new managerial practices, which have enabled organizations to more effectively use computers. For example, in part because of social science research, many managers now recognize that one must redesign incentive systems to encourage sharing information if they want to make best use of new technologies that support organizational memory.

(3) This research has also informed public debate about priorities for investment in computer systems at both the organizational and national levels. This research, for example, provided theory and data that supported the public debate on the productivity paradox in National Academy reports and in the business press.

There is a variety of research which fits under the rubric of the social impacts of computing, and which warrants attention in the future. This includes the impacts of information and computer/communications systems at all levels of modern society from the group to the organization to the community and society. It includes issues such as the productivity payoffs from investments in IT; the use of new technologies such as the Internet, the World Wide Web, and multimedia; the economics of information; and information policy issues such as universal access, pricing for internet access, privacy, security, vulnerability from growing dependence on computing networks. It also includes study of the impacts of the information industries on the economy, on regional economic development, on globalization of production, on industrial competitiveness, and on national defense.

Research in this area is vital to guide investment decisions. For example, research on the social impact of computer technology will form much of the basis of the technological impacts chapter of NSF's science indicators volume. The need for research of this type is growing. As computing moves from the world of business organizations and becomes essential to ever larger areas of human life, it is even more crucial that we understand how to apply it effectively. Much of the nation's massive investment in information technology for education, for health care or electronic commerce, for example, is likely to be wasted without a better understanding of the fit between computer systems and social systems. We need to develop better predictive models of the interaction of computer systems and human organizations that can be applied more systematically in developing and implementing new information systems. To give but one example, to effectively design information networks for education, we must more broadly understand how teachers, students, and computers can be organized for learning. Achieving this goal requires both empirical and theoretical efforts.

Moreover, the spread of computing creates a mandate for us to identify both its intended and unintended effects. As computer systems are more intensely used in more and more settings, we need empirical and theoretical research to describe and predict impact at the group, organizational and societal levels. At a minimum we need descriptive research that documents what rapidly changing computing environments, like the World Wide Web, were like at particular points in time and place, to serve as a baseline for historical studies of the impacts of computing. The more challenging goal is to develop better theoretical models that allow us to predict the social impacts of technology before they actually occur. The computational models of social organizations, described below, are one attempt to fill this need.

6.4. Multi-Agent Systems

Multi-Agent Systems/Distributed Artificial Intelligence (MAS/DAI) is an emerging research focus in CSS. Multi-agent systems are computational systems in which several artificial 'agents' interact or work together over a communications network to jointly perform some set of tasks or to satisfy some set of goals. MAS/DAI systems may involve computational agents that are homogeneous or heterogeneous, with common or differing goals. MAS/DAI research focuses on issues of collective (as opposed to individual) level problem solving, interaction, and coordination.

MAS/DAI research is critical for effectively exploiting the increasing availability of diverse, heterogeneous and distributed on-line information sources, and as a framework for building large and complex distributed information processing systems. Multi-agent systems provide a potential model for computing in the 21st century in which networks of interacting, real-time, intelligent agents seamlessly integrate the work of people and machines. Agents in such networks need to be semi-autonomous and highly adaptive due to their "open" operating environments in which the configurations and capabilities of other agents and network resources are changing dynamically. Moreover, it is essential that agents in these environments be able to form and evolve higher-order social structures such as teams and organizations, to exploit collective efficiencies and to manage dynamic situations. MAS/DAI research is very timely because the enabling infrastructures being developed for mobile computing and interoperability among programs residing at distant sites will make the construction of multi-agent systems much easier and more widespread and will raise the importance of solving MAS research problems.

Application domains in which multi-agent system technology is being increasingly deployed exhibit a natural spatial, functional or temporal decomposition of knowledge and skill among agents. Examples of application domains which have used a multi-agent approach include: distributed situation assessment (e.g., network diagnosis, information gathering on the internet); distributed resource scheduling and planning (e.g., factory scheduling, network management, power grid control); and distributed expert systems (e.g., concurrent engineering). The need for a multi-agent approach can also come from applications in which agents represent the interests of different organization entities (e.g., in electronic commerce and enterprise integration). Another emerging use of multi-agent systems is in layered systems architectures in which agents at different levels in the architecture need to cooperate and negotiate to achieve appropriate configurations of resources and computational processing. The number of fielded commercial applications to date is small but growing quickly. Given (1) the tremendous interest in the field as exemplified by the attendance by both academic and industry at the recently initiated series of International Conferences on Multi-agent Systems (ICMAS), (2) the emerging infrastructure to support the building of applications, (3) the emerging need to grapple with issues of effectiveness, efficiency, and bounded rationality in collective, distributed information systems, and (4) the impact of computational theories of collective behavior in other fields, we expect the impact of Multi-agent systems to significantly increase over the next five to ten years.

The design, implementation, adaptation, and assessment of automated multi-agent collectives raises a number of specific research issues, many of which interact strongly with the other areas of CSS research as well. The major conceptual problem that MAS/DAI researchers face is the bounded-rationality of agents' computational capabilities and the possibility that the information an individual agent is using to make its decisions is incomplete, out-of-date, or inconsistent with that of other agents. In order to deal with the uncertainty that arises from this lack of appropriate information, and the lack of sufficient computational resources to fully process available information, a number of specific techniques, both formal and heuristic, have been developed. These include: coordination strategies that enable groups of agents to solve problems effectively through decisions about which agents should perform specific tasks and when, and to whom they should communicate the results of task execution; negotiation mechanisms that serve to bring a collection of agents to a mutually-acceptable joint state; techniques for conflict detection and resolution; protocols by which agents may communicate and reason about inter-agent communications; and mechanisms whereby agents can maintain autonomy while still contributing to overall effectiveness of the collective. Where formal techniques have been used, they have generally been based on game theoretic ideas, market mechanisms or logical formalisms, while heuristic approaches have their roots in knowledge-based AI search, planning and scheduling mechanisms. Conversely, MAS/DAI research has also helped advance cognate research areas such as game theory and economics, by beginning to put in place stronger, tractable algorithmic foundations and methods, and by presenting new areas of computational application for those theoretical areas.

In addition to these established research directions, researchers have also recently been expanding their focus to include issues of scale (from collectives involving tens of agents to those with hundreds and even thousands of agents), the development of generic, domain-independent rather than application-specific solutions, the development of formal analysis techniques for predicting performance, and to new theories of how knowledge, and interaction and organization can be constructed in social collectives. Underlying all this work is an attempt to develop a conceptual understanding from a computational perspective about the nature of knowledge, interaction, and coordination in both large and small social systems and among both benevolent and self-interested agents.

6.5. Computational Organization Theory

Developing a better understanding of organizations as computational entities is important if we are to improve and better manage them. Researchers in the area of Computational Organization Theory (COT) use mathematical and computational methods to study both human and automated organizations as computational entities. Human organizations can be viewed as inherently computational because many of their activities transform information from one form to another, and because organizational activity is frequently information-driven. Computational Organization Theory attempts to understand and model two distinct but complementary types of organization. The first is the natural or human organization which continually acquires, manipulates, and produces information (and possibly other material goods) through the joint, interlocked activities of people and automated information technologies. Second, COT studies artificial computational organizations comprising multiple distributed agents which exhibit collective organizational properties (such as the need to act collectively, an assignment of tasks, the distribution of knowledge and ability across agents, and constraints on the connections and communication among agents). Researchers use computational analysis to develop a better understanding of the fundamental principles of organizing multiple information processing agents and the nature of organizations as computational entities.

The general aims of research in this area is to build new concepts, theories, and knowledge about organizing and organization in the abstract, to develop tools and procedures for the validation and analysis of computational organizational models, and to reflect these computational abstractions back to actual organizational practice through both tools and knowledge.

The basic vision driving research in this area has three components: (1) the scientific search for general principles of organizing that transcend agent type, and the search for limitations to such principles; (2) the development of computational tools that enable organizational engineering such as "what if analysis" tools to evaluate redesigns, new structures, the impact of new technologies, and the impact of new policies on the organization prior to making the actual change on the organization; and (3) the development of computationally based pedagogical tools for learning about organizing and organizations through simulation.

Research in this area has resulted in a large number of models, each with its own special characteristics. For example, one useful model of information-seeking, decision-making, and problem-solving activity in organizations is distributed search. Since formal computational models of search are well understood, modeling organizational activity as search can provide a clear and tractable explanatory framework. New approaches to control or task allocation in distributed search frameworks can, by analogy, provide suggestive new approaches to these problems in human organizations, e.g. in the development of new organizational forms or for reasoning about the effects of alternative strategic decisions. In the end, distributed search models provide just one type of abstraction that is useful for reasoning about problems of both human organizations and computational ones, and so help to unify thinking about both types.

Typical COT research is concerned with issues of collective performance, social and shared cognition, team mental models, group information processing, and concurrent information analysis arise. Research progress in this area is typically made by multi-disciplinary teams working to develop and validate models of organizations that are grounded in empirical data. To date successful computational theorizing has been done by medium sized teams (3-7 individuals) working over multiple years (2 to 5) often working in multiple universities and sometimes in industry. Validation of models is an on-going process and is often done by other teams, often drawing on researchers in other fields, and may not involve the model developers.

Computational techniques such as simulation can be used to bootstrap our understanding of the computational organization. There is little doubt that for the organization theorist computational analysis is an invaluable tool for theory building and examining issues of organizational dynamics, because it enables the researcher to generate a set of consistent theoretical propositions from basic principles even when there are complex interactions among the relevant factors. Organizations are inherently complex, non-linear and adaptive systems in which organizational action is the result of interactions among adaptive systems (both human and artificial), of emergent structuration in response to non-linear processes, and of detailed interactions among hundreds of factors. Such systems are generally not analytically tractable and so they must be examined using computational techniques simply to think through the possible ramifications of such processes and to develop a series of consistent predictions. Additionally, computational models allow researchers to show proofs of concept and to demonstrate minimal active models that provide theoretically-plausible explanations of phenomena. In this way, computational models can be used to show the potential legitimacy of various theoretical claims in organization science.

Computational analysis, however, is not simply a service to organizational theorizing; rather, computational organizational theory is actually pushing the envelope in terms of computational tools and techniques. Computational organizational models are grounded operational theories. In other words, unlike traditional DAI or multi-agent models, COT models draw on and have integrated into them knowledge from organization science about how human organizations operate and about basic principles for organizing. In these models, the traditional distinction between normative and descriptive models often becomes blurred. For example, the models may be descriptive at the individual level, describing individuals as bundled rational, with various built in cognitive biases, but normative at the structural level, finding the best organizational design, subject to a set of task based or procedural constraints. Further, in order to adequately model organizations work in this area often has to explore issues of general concern within computer science such as shared knowledge representation, communication protocols among multiple agents, coordination of multiple agents, and agent adaptation.

Computational organization theory has an interdisciplinary history drawing on work from a variety of computational disciplines including: research in distributed artificial intelligence (DAI), multi- agent systems, adaptive agents, organizational design and learning, social networks, and information diffusion. One of the earliest and best known works is which uses a simple information processing model to address issues of design and performance is Cyert and March's *A Behavioral Theory of the Firm* from 1963 [3]. Many computational organizational theorists use complex adaptive approaches or optimization approaches, such as genetic algorithms, genetic programming, neural networks, and simulated annealing to answer questions about organizational change, adaptation, learning, and evolution. Much of this work demonstrates the importance of history and path-dependence; i.e., that the path the organization follows as it evolves affects how well it performs. In other words, there are often interesting interactions between agent architecture, the way agents are coordinated, and the way the agents and the coordination structure adapt and change over time.

Among the main research issues in this area are: developing computational tool kits for designing and building computational models of organizations, teams, and social systems (e.g., an agent oriented language with built in task objects and communication); developing multi-agent logics; determining the appropriate protocols and standards for inter-agent communication (regardless of the level of cognitive capability held by the agent); determining what coordination structures are best for what types of agents and tasks; developing intelligent tools for analyzing computational models; determining whether hybrid models (such as a joint annealer and genetic program model) are better models for exploring organizational issues; exploring the ways in which different types of learning, adaptation and evolution interfere with or complement each other; emergence of new organizational forms; developing measures of organizational structure; exploring the existence of, or limitations of, fundamental principles of organizing; developing managerial decision aids based on computational organization models; exploring the trade-offs for system performance of task- based, agent-based, and structure-based coordination schemes; development of validation procedures, protocols, and canonical data sets; representation of information and communication technology in computational models.

A better understanding of the fundamental principles of organizing multiple information processing agents and the nature of organizations as computational entities, along with the development of computationally based decision and training aids, has the potential to:

(1) Decrease the cost of management through better tools for redesign and re-engineering,

(2) Increase the efficiency and effectiveness of networks of artificial agents,

(3) Provide a computational testbed for examining the impacts of new information technology on organizations, and

(4) Enable organizations to erect guards against information warfare.

Research in this area is already having an impact in industrial settings. For example, some systems developed by COT researchers are being used as decision aids to help in corporate re-engineering.

The level of interest in this field is high and increasing steadily. Signs of this interest include:

(1) The development of a new journal dedicated to this area - Computational and Mathematical Organization Theory,

(2) Increasing academic and industrial attendance at annual workshops,

(3) The development of European conferences on this topic,

(4) The increased number of sessions at disciplinary conferences on this topic, and

(5) The increasing demand by publishers for textbooks in this area.

Research in this area is re-shaping the way we think about organizational learning and adaptation. It is leading to measures of organizational design and performance that can then be used by those interested in the social impacts of computing to examine how the technological change alters the form of organizations.

VII. Impacts of CSS Research

Historically, research in CSS has led to important contributions to computer science, to new approaches to organizing, to understanding the social impacts of information technology, and to the design of new large scale systems. Research sponsored by the ITO Program in particular has played an important part in those contributions through support of basic research. The following examples illustrate some of those impacts:

The National Science Board has established a new chapter in Science and Engineering Indicators, the NSF's annual review of the state of science and engineering in the US. This chapter addresses the social and economic implications of technology change, with a focus on information technology. The research supported by grants already provided from ITO provides a strong historical basis for this new chapter, and the CSS community provides the body of expertise needed to carry it forward.

Research on mechanism design, organized systems, and coordination theory in research groups that have been supported in part by ITO is estimated to have had positive financial impacts on power management, SEC auctions, and electronic commerce far exceeding the total of all NSF investment in the ITO program since its inception.

Research on computer supported cooperative work has led to findings for the more efficient and effective design of work teams in environments as diverse as the shop floor of manufacturing plants to the professional teams in consulting firms.

The application of collaborative technology to basic science has had dramatic impact on the productivity of scientists and researchers, the sharing of measurement instruments, and the sharing of databases for both scientific and policy analyses.

In addition, each of the areas discussed in the previous section, "Sub-areas of Research," discussed examples of impacts and potential impacts.

VIII. NSF Action to Support the Research Agenda

As illustrated by the earlier discussion of research results and impact, research on CSS has been a tremendous success with the value of the research far exceeding the cost. While the field is healthy and growing, we are concerned about the future of CSS research and the community, and feel that NSF should play an aggressive role in support of research and graduate education in CSS. The following points outline that role:

8.1. Strong Anchor and Leadership in CISE

Within NSF, research on CSS has traditionally been supported by grants from ITO within the IRIS Division of the CISE Directorate. This is appropriate because of the field's central concern with computation and information processing in organized systems. The object of study - Computation and Social Systems - is inherently computational. It encompasses information processing by intelligent agents, human agents and organized systems of such agents including a mix of artificial and human agents. Such systems cannot be understood without consideration of their contexts, especially the social contexts of their construction, use and impact. For this reason, explicit consideration of the social aspects needs to be an integral part of research into computation and information processing. Consideration of the social aspects separate from the computation and information processing aspects would not bring about the integration required for "engineering" the social impacts of multi-participant information systems.

Further, funding under one organization such as ITO is the most appropriate model for administering grant programs for CSS rather than distributing the administration to multiple units or programs. Distribution of funding would only create confusion within the research community and might lead to conflict rather than cooperation between programs within NSF. A clear distinction and division between programs actually facilitates cooperation.

However, this one organization can and should encourage joint funding with other entities within NSF and elsewhere. There is critical corollary knowledge, content, communities and methods related to computation and social systems in the Social Sciences and in other disciplines and, therefore, there should be active cooperation with the other disciplines. It is evident that this cross-foundation cooperation is historical reality and is growing productively.

8.2. Vigorous Support for Research

As indicated earlier in this report, we feel that in order to advance the research agenda outlined above, more funding is needed for CSS research. Funding should be devoted to the areas identified above, as well as new areas that will emerge to be important but which cannot now be foreseen.

Moreover, NSF funding should be leveraged. It can be leveraged by joint funding with other units within NSF. It can be leveraged by joint funding with other government agencies; and, it can be leveraged by joint funding with private industry.

Priority should be given to investigator-initiated proposals, involving both individual and multiple investigators and both multidisciplinary and interdisciplinary research. There should also be opportunities for CSS-initiated calls for proposals, especially in areas where there is clear need for research but the community is not currently active or moving at the pace required.

Finally, there is need to bring together a critical mass of researchers and funding in some areas so that breakthroughs can be made in resolving key challenges and issues in the field. Towards this end, NSF should work to encourage the creation of several national centers with new funding to take on these challenges. It is the strong feeling of the CSS community that such center funding must be in addition to, not in place of, investigator initiated proposals. Such national centers are also a way to leverage funding both within NSF and within private industry.

8.3. Active Collaboration within CSS and Outside

There is a lot of synergy to be achieved among the disparate communities that make up CSS. There is a lot of information that could be valuable to the individuals and groups that work within CSS. It is important for NSF to provide means for cross-fertilization, sharing of instrumentation, sharing of information and sharing of human expertise. These objectives can be achieved by several mechanisms which we encourage CSS to vigorously promote:

Workshops among existing grantees. There is a great need for means by which current grantees can share methods, data and findings; look at new challenges and issues in the field. These include: (1) assess and synthesize the state of knowledge in CSS subareas; (2) identify new research opportunities and challenges; and (3) engage in professional interchanges and exchange of experiences.

Workshops, fellowships, and grants for prospective community members. If the CSS community is going to remain vigorous and healthy, there is also a need to encourage people other than the current grantees to be brought into the community. Such people include new Ph.D. graduates, post doctoral students, women and minorities, and those working in reference disciplines outside of CSS. Workshops, postdoctoral fellowships and small grants are mechanisms for bringing such people into the community, and should be used more fully.

Facilitation of interdisciplinary research. Most important of all, there is a need for support of multidisciplinary and interdisciplinary projects, for helping individual researchers to become interdisciplinary, and for developing doctoral students with interdisciplinary skills. Here, new kinds of grants and awards, and supplements to grants, are required which permit doctoral students to receive part of their training at one university and part at another, which enable some universities (or individuals) to offer specialized facilities and training for other universities, which build large databases required by the community such as a database on organizations or on the information industries, which build specialized facilities such as experimental laboratories, and which facilitate collaborative research using these databases and laboratories.

Support of international research. Finally, there are opportunities for greater international cooperation and collaboration in CSS research. This is especially true where different countries present different models of computation or of social systems which have relevance for computation and social systems in the U.S. Such research is also important for gauging progress, for examining strengths and weaknesses of U.S. science, and for ensuring continued U.S. leadership in the computer and information science disciplines.

8.4. Dissemination of research results

Bringing in the social aspects of the technology makes research in CSS inherently interdisciplinary, which has several implications. The first is that it is necessary to reach out to other scientific communities and disciplines for theories, models and principles for the design, construction, use and impact of these systems. It is insufficient to simply borrow from these disciplines. Practitioners must be involved in the research. It also means that CISE should make greater use of joint funding with other divisions of NSF such as the Social, Behavioral and Economic Science. CISE should also make greater use of joint funding with other federal agencies such as the Department of Education, Department of Energy, and DARPA. This will further encourage dissemination of research results (and testing them) to user communities.

IX. Summary and Conclusions

The field of Computation and Social Systems is healthy, the community is growing, and past research supported by NSF and others has produced significant results which have had strong impacts in the scientific community and in society. Although the fundamental objects of concern - interlinked information technology and social systems - have not changed, the manifestations have changed with the rapid evolution of new technologies (e.g. low cost multimedia home computers), new uses of the technology (e.g. the world wide web), new forms of organizations (e.g. value added partnerships and virtual organizations), and changes in information related institutions and industries. These changes bring about new questions and new opportunities; therefore much remains to be done to better engineer effective, widespread information technologies and their social impacts.

Today, this field is characterized by a rich multidisciplinary community including computer scientists, management scientists, economists, and social scientists. It is also characterized by multiple streams of research which converge around the central theme of the mutual structuration of information processing and social systems. Many of the researchers in this field have taken the bold step of working on hard problems at the fringes of their disciplines. Also, many have sought to form interdisciplinary alliances with different disciplines to attack some of the challenging socio-technical issues that arise in this field. We believe that this field has, and will continue to have significant impact. Recognizing that these interdisciplinary explorations are difficult, we strongly recommend enhanced incentives, strengthened partnerships across NSF programs and between researchers and industry, and increased funding for these critical research activities by NSF and other organizations.

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