Organizations in Multi-Agent Systems

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Abstract. The aim of this paper is to illustrate and sensitize reader to the variety of perspectives and the fundamental nature of organizations as stable/stabilizing systems and as multi-perspective action systems. Researchers have been explicitly thinking about MAS/DAI organizations and attempting to link formal (human) organization theory with MAS/DAI models for at least twenty years. Despite this, the idea of organizations has been a peripheral theme in MAS/DAI research---primarily a specific coordination technique---not really one of the central intellectual issues of the field. The theory of 'natural' organizations has a somewhat longer, more diverse, and more thorough intellectual history than that of organizations in MAS. Beyond recent work in human social and organization theory, some newer research on abstract organizations has been attempting to unify concepts in biology, chemistry, physics, mathematics, and computing theory (e.g., the lambda calculus), with those of natural social organizations and multi-agent systems. The landscape for thinking about organizations in MAS is growing quite interesting, and this paper surveys this landscape. It presents and contrasts some conceptions of organization that have emerged and proven useful, and attempts to show how these have been implemented, experimented with, and applied. It also projects some future directions for research on MAS organizations, and gives some thoughts on where the most exciting issues lie.

1 Introduction

The aim of this paper is to illustrate and sensitize reader to the variety of perspectives and the fundamental nature of organizations as stable/stabilizing systems and as multi-perspective action systems. It's not news that information and computation are rapidly becoming ubiquitous and embedded parts of modern life in all spheres. To name just a few:

- The physical environment: smart buildings, roads, buildings, nanomachines, and 'smart matter'
- Critical infrastructures: energy/power distribution, telecommunications, transportation/logistics, intelligent HVAC, digital libraries, etc.
- Healthcare: biocomputing, patient records, non-invasive instruments
- Daily life: wearable computing, home networks/smart houses, personal information management.
- Science and engineering: embedded instrumentation, large-scale automatic instrumentation and data gathering, distributed experimentation, computational grids.

Establishing the principles and tools for understanding and organizing this growing fabric of information and computing is one of the next critical frontiers for the information and computer sciences.

With the growth of this fabric, especially those parts driven or inspired by the Internet, interest in high-level, modular, and data/knowledge-rich computation frameworks including client-server frameworks, peer-to-peer interactions, and 'agents' is exploding. Many people share a vision of ubiquitous embedded computing, information webs, knowledge networks, digital libraries, or electronic commerce environments that are very active, populated with roving, dynamic information management agents and teams. They imagine the capability of easy, seamless integration of heterogeneous modular units: teams of agents forming and reorganizing at will, to respond to new information management and retrieval tasks, new economies of information, new ways of consolidating information. etc. They imagine agent collections easily integrating new 'team members' and re-coordinating themselves for robust, efficient performance as new services, skills or operating conditions appear.

And this vision doesn't stop with information-oriented environments and applications---action in the world is also part of the newest scenarios. The vision of "information appliances" promulgated by Hewlett-Packard, Sun, Cisco, Microsoft, and others through technologies such as "Javaspaces," "Jini" and "Universal Plug and Play" includes physical appliances such as toasters and HVAC, entertainment appliances, and so on as active, self-organizing components of a huge, interactive network-based fabric.

2 Critical Barriers and Knowledge Gaps

In large measure, the systematic scientific principles and robust coordination technologies that will help this vision to unfold effectively and with comprehensible, predictable operational character don't exist. From a scientific standpoint, there are a number of barriers. From the standpoint of this paper---organizations in MAS---the critical barriers include the following:

- We have relatively limited principled understanding of how to organize sophisticated, interdependent, heterogeneous, semi-autonomous computational objects--and the infrastructures to support them---into aggregates with stable, predictable, and reliable behavior at a very large scale.
- More than simply achieving stable reliable behavior in collectives, the point of formal MAS organizations is to achieve economies of scale and scope by exploiting features such as division of labor, integrated coordination, and distributed commitment. We have limited principled knowledge of how to create and exploite the theories and techniques that will create such added efficiencies, yet it is absolutely essential to do so as the rate of resource consumption (e.g., the resources of information search, interpretation, assimilation, application, communication, etc.) increases faster than our ability to provide it.
- We lack the practice and experience in building and operating such organizational systems in situ.

From a scientific standpoint, the foundations of this vision have a long history. For over thirty years, a multidisciplinary community of researchers and developers has been exploring new paradigms of information, knowledge, problem-solving, and activity that are based on group, team, organizational, and social-level approaches. This research uses computational models, metaphors, representations, and research tools to build and test theories and mechanisms for dynamic, coordinated, interactive computing. It has incorporated (and added to) knowledge from fields including information/computer science, economics/game theory, organization theory/social science, and even ethology to name a few. Over time, the subjects of this research field have been variously called "Agents", "Multi-Agent Systems" (MAS), "Coordinated Computing," "Coordination Theory," "Distributed AI," and so on.

The thrust of this paper is to begin to illustrate some of the issues that should be placed at the forefront of thinking about organizations as a critical issue for the future of MAS. Researchers have been explicitly thinking about MAS/DAI organizations and attempting to link formal (human) organization theory with MAS/DAI models for at least twenty years. Despite this, the idea of organizations has been a peripheral theme in MAS/DAI research---primarily a specific coordination technique---not really one of the central intellectual issues of the field. The theory of 'natural' organizations has a somewhat longer, more diverse, and more thorough intellectual history than that of organizations in MAS. Beyond recent work in human social and organization theory, some newer research on abstract organizations has been attempting to unify concepts in biology, chemistry, physics, mathematics, and computing theory (e.g. the lambda calculus), with those of natural social organizations and multi-agent systems. The landscape for thinking about organizations in MAS is growing quite interesting, and this paper surveys this landscape. It presents and contrasts some conceptions of organization that have emerged and proven useful, and attempts to show how these have been implemented, experimented with, and applied. It also projects some future directions for research on MAS organizations, and gives some thoughts on where the most exciting issues lie.

3 Perspectives on Organizations in MAS

There are three orientations commonly taken with respect to organization in MAS research: Theoretical, phenomenological, and technological.

Theoretical Orientation: A *theoretical orientation* attempts to define and delimit the general concept of organizations, to establish taxonomies and varieties of possible organizations, and to make general statements about organization, organizing processes, and organizations, in the abstract. From this orientation, organizations may or may not exist a priori. The properties of organizations as abstract types is the main point of interest. The information processing aspects of organization and organizing are, then, very compatible with computational approaches to theorizing about organizations, because both can be treated productively using common abstractions.

Phenomenological orientation: A *phenomenological orientation* attempts to describe, model, and explain existing, observable organizations as phenomena to be accounted for. From this viewpoint, organizations exist, and researchers need to explain how and why they come into being and persist. Phenomenological theories attempt to account for the observed properties of naturally-occurring organizations. Since phenomenologists build models, computational tools and modeling techniques are useful, even to the extent that they predict or explain fundamental limits and thus help to account for the actual behavior or structure of observed organizations. But for phenomenologically inclined researchers, the ending point is what can be observed in the natural world, not what are the abstract theoretical possibilities for organizing.

Technological Orientation: A number of organization scientists and economists have argued that natural organizations (as well as other social forms) come into being as large-scale problem solving technologies to deal with circumstances that otherwise couldn't be handled because of the limitations of individual actors [Simon 1996, Malone 1987, Carley and Gasser 1999]. (Note that this class of explanations typically assumes a prior existence and character of individual agents from which organizations are comprised, and whose limitations are addressed by organizing. It is essentially a reductionist viewpoint in that it doesn't account for organizations themselves as fundamental entities, nor for agents that emerge from collectives, nor for agents and collectives that mutually construct each other in a "circular" fashion. See, e.g., [Gasser and Ishida, 1991; Giddens, 1984]; also see below). Limitations to be overcome by organizing may be of several types:

Cognitive Limitations: bounds to the rationality or computational tractability of information processing in individual agents create pressures for collective action to achieve ends with more extensive cognitive or computational requirements.

Physical Limitations: Bounds on physiology, resources, and access across space and time create pressures for comunication and binding among multiple agents to extend action, perception, and access to resources across broader regions of a space that is accessible to individuals.

Temporal Limitations: Bounds on agent lifetimes create pressures for collective action across time when the temporal span of action extends beyond the lifetimes of agents.

Institutional Limitations: Individual actors are limited in legal, political, economic, and other institutional senses. Collective action can modify the insitutional status of individuals and can create new institutional-level actors with status specialized for institutional-level tasks [Carley and Gasser, 1999; Powell and DiMaggio, 1991; Scott, 1995].

Large construction projects, for example, require moving amounts of material over great distances---needs that are far beyond the capabilities of individuals alone. Economies of scale and scope gained by organizing activity through space and time are what make large projects possible. Thus, technological orientations see organization and organizing processes fundamentally as technologies to achieve ends such as efficiency, scale-of-effort, complexity management, or human systems integration. From this viewpoint, organizations are a kind of social technology that can be put to use in selected contexts to accomplish some designable but supra-individual end.

This set of three orientations---the theoretical, the phenomenological, and the technological---begins to give us a handle on how to frame existing MAS research on organizations by considering the goals and assumptions of the researchers and the kinds of issues that can be understood. They are not necessarily mutually exclusive. For instance, organizational phenomenologists create models and explain phenomena, and these models and explanations may draw n abstract theory or on technological explanations.

4 Analysis of Critical Organizations Concepts

We will not attempt to give a precise or exhaustive definition of organizations here, but instead will aim to capture a number of characteristics that are on the one hand, typical of organizations from an MAS perspective, and on the other hand, useful in recognizing, talking about, theorizing about, and building MAS organizations. First, organizations are structured, patterned systems of activity, knowledge, culture, memory, history, and capabilities that are distinct from any single agent. We say, then, that organizations and many organizational phenomena and characteristics are "supra-individual" phenomena: they exist at a level independent of specific individual behaviors or attributes, such as an aggregate level or as a type. We also insist on the fact that organizational explanations should be based on organizational (that is aggregate or other supra-individual) information or models. Organizations have relationships with other social[1] entities such as institutions and social groups. Finally, organi-

[1] In this paper, the term "social" means specifically a) occurring at multiple space-time locations simultaneously, b) involving multiple perceptual/analytical perspectives, and c) incorporating internal and external interdependencies and linkages. That is, "social" things happen concurrently in different places, they involve many different viewpoints or perspectives si-

zations have some "extent" across some abstract space. That is, they "take up" or "occupy" some region of a defining space such as geographical space (i.e., a physical dimension of organization), time, semantics, symbols, deduction, and so on. Several concepts are basic to considering organization. Not all of these concepts apply as clearly or as essentially to all organizations. Nonetheless, each of them serves to sensitize us to critical issues in thinking about organizations, especially from general, dynamic, and computational perspectives.

Division of activity types: activity in organizations is not uniformly or randomly distributed across an organization's defining space. Instead types of activity are differentially distributed, leading to the concept sometimes called "division of labor" for human organizations. Phenomenologically, we might say that activities can be segmented by type, and different activity types may be observed to occur with differential frequency in different regions of an organization's defining spaces. Technologically speaking, we can design organizations to exploit efficiencies derived from applying differential skills of participants and different stable mappings of skill sets to organizational goals or problems.

Integration: Organizations have interdependencies between different regions of activity in their defining spaces. That is, an organization is in some sense a set of constraints on the set of relationships between points in the organization's defining spaces. In addition, organizations are "whole" systems of information and activity, not just unstructured collections of parts and localized actions. Dimensions of organization are integrated, in the sense that they are aligned and interacting, not random and separate.

Compositionality: Organizations are structures that are composed of other structures through a variety of stabilizing and aggregative mechanisms (cf. [Fontana and Buss, 1996]). However, the assumption that organizations necessarily comprise composable atomic units such as "agents" or "individuals" isn't a fundamental aspect of organization. I take this position for two reasons: First, the notion of organization is fundamentally a supra-individual, collective notion. Properties of organizations that are properly termed "organizational properties" only exist at the aggregate level. Second, the notion of circular causality means that individuals are the product of organizing processes, both in a "bottom up and top down" sense, and in a lateral, collective sense [Gasser and Ishida, 1991]

Stability/Flexibility: Organizations exhibit patterns of activity and in fact one way to describe organizations both theoretically and phenomenologically is as observable

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multaneously, and their parts are linked and hence constrained both inwardly and outwardly. This is an abstract, structural sense of "social", not one specific to people, and it explicitly doesn't refer to affective dimensions typical of many human social activities. These are nonetheless important, especially in the context of organizations that integrate people and machines (e.g. [Scerri et al., 2000]). The requirement of "simultaneous multiple perspectives" is, for me, the most critical defining characteristic.

patterns of activity[2]. These patterns have stable features (the stable features is what makes them patterns) and they have flexible features (no two collections of organizational activity are ever the same, and in fact flexibility of action is important in dynamic environments). In effect, then, organizations can be seen as architectures: stable, constraining structures within which a certain degree of flexible activity is possible. Generalizing to multiple dimensions of organizational description, another way of saying this is that organizations are "specific collections of settled (stable) and unsettled (flexible) questions" (see below and [Gasser et al., 1987]).

Coordination: If organizations are to effect economies of scale and scope, they must have efficiencies beyond the simple aggregate sum of the efficiencies of individual actors; they must be, in effect, resource amplifiers, increasing order within their operational scopes. [Ashby, 1962; von Foerster, 1960, Lendaris, 1964]. These efficiencies are made difficult due to the combined effects of interdependency and uncertainty. Collections of interdependent activities with multiple possible outcomes create regions of activity space with differential value. Efficiencies require optimization to activity patterns that fall into the highest-value regions, and are sustained there. Unfortunately, with uncertain local information about possible distributed outcomes, and with limited ability to affect distributed activities at-a-distance, convergence to high-value activity regions is difficult. In physical systems, interactional uncertainty is manifested through the statistical mechanics of dynamic multi-body systems, yielding aggregate-level relationships and "laws." In systems where aggregate behavior measures are too gross to achieve the efficiencies required, subtler and more localized mechanisms are needed. This is the role of coordination techniques.

Supra-Individuality and Roles: Organizations are certainly specific, concrete activity systems that enact specific concrete actions in specific, situated locations and contexts. But, paradoxically, they are also activity systems structured through complex sets of activity types. The internal linkages that "glue" and stabilize organizational activity are founded on actors' ability to generalize from specific instances of interactive behavior to prototypical types of behavior, to develop interlocking commitments to and expectations of those behavioral types, and finally to actualize or realize new instances of joint activity that correspond with those types. The repeated re-enactment of activity of known types reinforces the structure of the organization in ongoing ways, and the organization continually remakes itself in action. (See Figure 1.) Weick has used the term "double interact" to describe a patterned, interlocking dyadic (2-agent) activity unit, from which he suggests all organizations are built [Weick, 1979]. Similarly, Giddens notes the continual process of reconstitution that builds social collectives [Giddens, 1984]. Similar cycles of autocatalytic reproduction are theorized as foundations of biological self-organization [Eigen and Schuster, 1979; Fontana and Buss, 1996].

A key aspect of the generalization, typing, and realization cycles that constitute organizations is that they are collectively consensual. The generalizations to activity

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[2] From the technological perspective, the core problem is how to link desired aims to specific mechanisms that create appropriate, efficient patterns of activity---how to get the "right" patterns of activity.

types are fundamentally organizational phenomena, not agent-level phenomena, in the sense that no single agent can assert a specific generalization or 'meaning' of activity, and hence no single agent can assert or sustain a commitment or expectation that involves such a generalized activity type. The understanding and expectations built into these activity types are spread through the organization. What this means is that organizations are supra-individual---they exist above and beyond single individual agents that may constitute them---and agents are replaceable into and out of types.

Another key aspect of activity types is that they capture the generalized properties of linkages among activities. All organizational activities are structured and constrained. These structures and constraints are also generalizable into types. To describe an activity type, it is also necessary to describe the "standard" set of linkages between the activity type and other activity types (and indeed linkages to other organizational aspects besides activity, such as information, resources, context, etc.) This means that activity types are inherently linked or distributed entities as well.

Another word commonly applied to a generalized activity type is "role" (e.g., [Nagendra Prasad et al., 1996]). Role typically describes an organizationally-sanctioned (i.e., consensually defined) structured bundle of activity types. Since an activity type naturally incorporates linkages and constraints that connect instances of it to other organizational aspects, it is natural to see a role as the abstraction of a position in a stable (i.e. generalized, repeatedly reinforced) set of relationships. This is the approach taken by Social Network theorists [Wasserman and Faust, 1994]. Roles are thus clearly supra-individual constructs because they consist of activity types, not to concrete, specific individuals, which can be replaced.

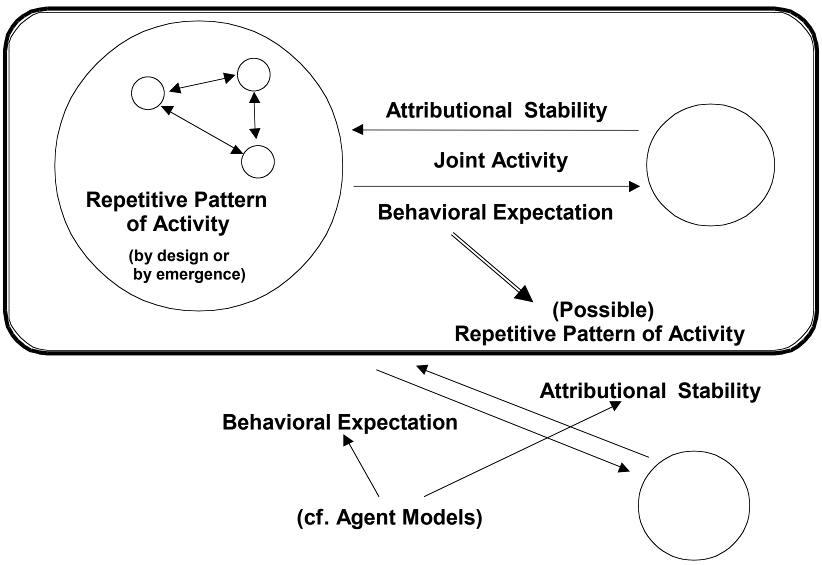

Figure 1: Organizations as Activity Patterns

Recursivity: Organizations are often composed of sub-organizations, and/or of multiple overlapping structures. In particular, the cascaded repetitive patterns of activity depicted in Figure 1 appear at multiple levels of analysis. This means that the phenomenology of organizations has a recursive character, and we would like theories and technologies of organization also to account for and make possible recursively structured collectives [Strauss, 1993; Fontana and Buss, 1996]

Multi-Level Representation and Causality: Organizations comprise multiple overlapping multi-level structures. The activities which constitute organizations form patterns in multiple scales of time, space, and other dimensions. Hence the patterned structures of organization interact with each other, and they interact with the environment of the organization, at multiple levels. Because of this, causality in organizations is a multi-level phenomenon. For example, in Durfee, Lesser, and Corkill's classic model [Durfee et al., 1987; Corkill and Lander, 1998], organization is seen as a long-term temporal commitment to sets of activities. These activities are also organized into short term reactive cycles and medium-term planning cycles, each of which is contextualized by the longer-term cycles that embed it. Thus concrete behavior emerges from three interlocking levels of repetition, and can be affected by changes in any of these levels. New technologies for experimenting with agent-based computational organizations also explicitly capture both nested temporal cycles and interlocking, multilevel activity patterns. The creators of the RePast modeling testbed, for example, describe it like this:

> "The name Repast is an acronym for REcursive Porous Agent Simulation Toolkit. Our goal with Repast is to move beyond the representation of agents as discrete, self-contained entities in favor of a view of social actors as permeable, interleaved and mutually defining, with cascading and recombinant motives. We intend to support the modeling of belief systems, agents, organizations and institutions as recursive social constructions." [RePast, 2001].

The MACE3J/TaskModel platform [Gasser, 2001a] also incorporates multilevel, recursively modeled structures of mutually-defining activities. On the theoretical side, see also [Buss, 1987; Fontana and Buss, 1996; Wilson and Sober, 1994].

Potentials and differentials: In physical systems, particular balances of attractive and repulsive forces yield particular organizational structures and dynamics. Ferber, among others, has exploited this simple attraction/repulsion ordering technique in experiments [Ferber, 1999] with interesting results, and it is a foundation of many abstract models of self-organization systems [Nicholis and Prigogine, 1985]. Organizational actors shape their activities with varying degrees of information and varying degrees of influence on other actors. In addition, the cycles of generalization, interaction, and realization noted above create differentials of expectation, commitment, and flexibility as generalizations have wider or narrower scope, or are more or less strongly reinforced through re-enactment. Such differentials affect how activities can be carried out and how interdependencies can be managed. They also lead to singularities and non-uniformities in structure that can take hold and serve as organizing anchor points [von der Malsburg, 1990]. Power, for example, is generally described as the ability to influence the behavior of an organizational unit or organizational actor. In general, organizational patterns are mediated by many such force differentials.

Rules and Grammars: It is a commonplace in the theoretical and phenomenological literature that organizations are rule-governed structures [Manning, 1977; March et al., 2000]. More recently, some theorists have begun to consider organizations as individual points in spaces of potential configurations of activity and process. They have begun describing these configuration spaces using grammars, sometimes with and sometimes without the attachment to some kind of "deep structure" that is common in linguistic grammatical theories [Pentland, 1995; Pentland and Reuter, 1994; Salancik and Leblebici, 1988]. Rules have three complementary interpretations in the theoretical literature on organizations:

- Rules as structures for action--that is, as procedural specifications
- Rules as constraints on action--that is as architectures of what is possible and what is proscribed
- Rules as compiled experience [March et al., 2001]

Grammars of organization are also interpreted under these three views. Ideally, a rule-based or grammar-based concept (and even implementation) of organization would make computational treatments of organization all the easier, as the theoretical and technological base for them is strong in computing. Unfortunately the dynamic, emergent, evolutionary, and situational aspects of both organizational grammars and organizational rules are also interesting and not well investigated. Manning, for example [Manning, 1977] presents a compelling analysis of high fluidity in the practical application of rules in organizations. In his view this fluidity comes about due to situational aspects of rule interpretation: all rules need interpretation in their application and the situated nature of their interpretations undermines their strategic, stabilizing, and patterned aspects (not to mention their potential status as "organizational procedures"). This disruptive in-situ character is a fundamental aspect of all distributed information semantics, not just of rules [Gasser, 1993]. However, it means that the account of rules and grammars as part of the fundamental character of organization needs expansion.

Uncertainty: Distribution of information necessarily introduces uncertainty into an information-mediated action space. The uncertainty is due to limitations of communication as well as to the concurrent nature of organizational activity. In addition, numerous systems exhibit inherent stochastic properties at the collective and individual levels. The effect of uncertainty in organizational systems is to limit the ability for activity systems to guarantee convergence to regions of activity space that exhibit high value. Thus, many technological strategies for organizing take the approach of expressly managing uncertainty as a coordinating function. This creates requirements for technologies (and theories) for uncertainty capture, representation, and reduction, in organizational systems. Chemical catalytic systems, for example, exploit the ability of catalysts to physically orient several molecules toward each others' binding sites. This reduces the uncertainty that reactions will take place (i.e. it increases reaction probabilities) and forces the aggregate reaction behavior toward an equilibrium more saturated with reaction products than without catalysis (cf. [Eigen and Schuster, 1979; Fontana and Buss, 1996]). Analogously, MAS organizational models that expressly deal with uncertainty (e.g., those of V. Lesser, N. Carver, and T. Wagner) attempt to focus global effort on most promising directions by reducing probabilities of poor local choices. This is accomplished via communication of intentions and meta-level information, and by local dynamic adaptation as new sources of uncertainty (or new information that reduces uncertainty) is discovered in real time.

With these analyses of organizations concepts in mind, we turn to the most productive current arena for studying and developing them further: Computational Organization Research.

5 Computational Organization Research (COR) as a Venue for Studies of MAS Organizations

Computational methods may provide several advantages for studying and enhancing organizational phenomena. Organization theory, analysis and design problems can be hard because of the scale and complexity of both the objects of study (organizations and organizational processes) and of the theories themselves. The epistemological, structural and configuration problems of organizations are at least as impactful as analogous problems that appear in other disciplines that regularly employ computational methods in similar ways. For the study of organizational issues, the foundation of theory, modeling technology and infrastructure is ready, and the impact of improved knowledge and effectiveness and flexibility of organizations could be quite significant.

Research in this area draws on work in distributed artificial intelligence (DAI), multi-agent systems, adaptive agents, organizational theory, communication theory, social networks, and information diffusion. One of the foundational works in this area is The Behavioral Theory of the Firm [Cyert and March, 1992] in which a simple information processing model of an organization is used to address issues of design and performance. While the strongest roots are in the information processing literature [Simon 1947; March and Simon 1958; Thompson, 1967; Galbraith, 1973; Cyert and March, 1992] and social information processing traditions, current models also have roots in the areas of resource dependency, institutionalism [Powell and DiMaggio 1991; Scott, 1995], and symbolic interactionism [Gasser, 1993; Gasser, 2001a]. Formalisms and specific measures of organizational design are drawn from the work in the areas of coordination [Malone 87], social networks [Wasserman and Faust, 1994] and distributed control [Corkill, 1983; Durfee et al., 1987].

Computational Organization Research (COR) can be examined along three axes:

Computational: The focus of this activity is explicitly computational approaches to organizational phenomena, including models and representations of organizational features and concepts such as those treated above. Of particular relevance to MAS, COR focuses on computational organizations, namely those made up entirely of computational entities such as agents and mult-agent aggregates.

Organization: The locus of this activity is typically both mid-range organizational-level phenomena in which aggregate, statistical models and theories take a back seat to detailed, behavioral accounts, and macro-scale phenomena that rely heavily on aggregate and statistical properties and behaviors. This line is sometimes hard to draw, and the issue of macro-mezzo-micro links is often of explicit theoretical and practical interest.

Research: The locus of COR activity is primarily organizational research, that is, innovations in description, analysis, theory, and methods. It is clear that much good organization research, especially that which occurs under the phenomenological and technological frames described above, is driven by clear applied problems, and that the best practical organization analysis tools embody clear principles and theory. This line, too, is hard to draw, and COR may include issue in the practical application of organizational tools.

COR is also timely at this point due to a convergence of several trends in computing and in organizations. In the aggregate, the impact of these trends is shown in Figure 2 and described below. Main points of convergence include:

- New kinds of information-based, networked organizations such as virtual organizations provide new classes of study objects (literally, "computational organizations" and new simulation, experimental, and information gathering technologies.

- Representation and implementation technologies and theory have advanced to the point where it is possible to capture complex organizational fundamentals such as those referenced above.

- Advances in computer-aided design have created the tools to bring computer-aided organization design into reach. Computational modeling and evaluation of organization can support progress on computational organization design. Techniques of qualitative modeling, optimization, and search developed for other applications also can support computational organization design [Gasser et al., 1993; Jin and Levitt, 1996; Pentland, 1995].

- High-powered desktop computing creates demand for generally-available tools for organization monitoring, analysis, and design. These machines along with very fast high-performance simulations capabilities on supercomputers [Gasser, 2001a; Gasser, 2001b] add the capability to do complex analyses of very large systems with reasonable response times[3]

- Critical infrastructure also exists in the form of research collaborations among working groups, and transferable analytical and modeling software and data.

Figure 2 illustrates the current state of progress schematically. To be successful and useful, the ability to capture and model organizational phenomena such as those analyzed above should satisfy two thresholds. First, computational models must offer a degree of analytical power that places them in a different class of method than what was previously available. We would like to see COR models offer insights that are unachievable with other means. Second, the entry and use costs of COR approaches and models should be low enough to enable a critical mass of collaborating practitioners to develop communities of practice in research. This is because the scale of phenomena, models, data, and indeed the complexity of the conceptualizations of COR phenomena creates tremendous need for collaboration in COR research. Figure 2 illustrates the continuing trajectory of progress for COR models, from regions of high cost and low payoff, to the current state of marginally useful concepts, models, and

[3] For example, using the MACE3J system we have been modeling multi-agent organizations that enact complex, dynamic task networks. We routinely run simulations of 5000 agents, 10,000 tasks, 500 problem instances, and ca. 10 million messages [Gasser 2001a].

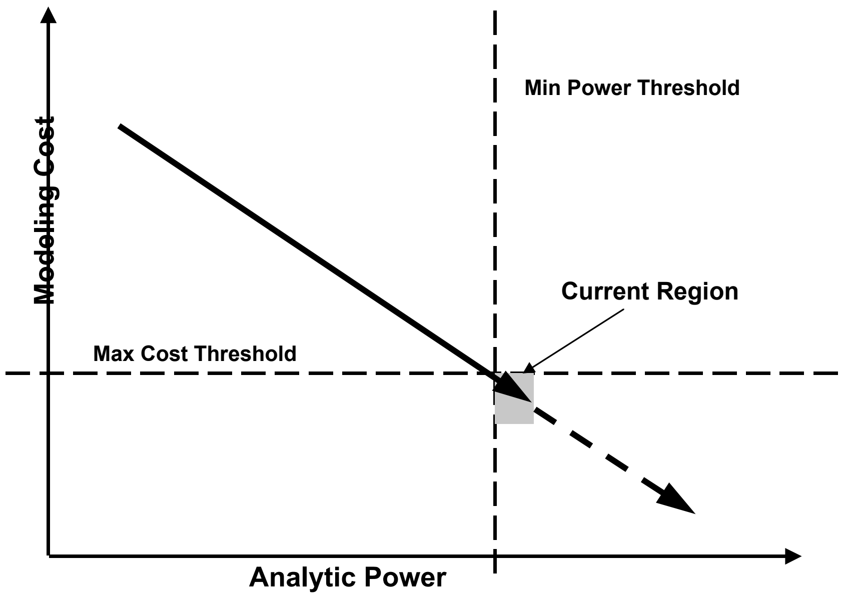

Figure 2: Computational Organization Modeling Prospects

infrastructure. Progress should occur rapidly as models and techniques proliferate from this point onward.

Another feature of current activity is the need to raise awareness of several fundamental assumptions of COR models, as follows. To be rational, COR researchers generally subscribe to the following assumptions [Carley and Gasser, 1999]:

- ***Modelability:*** Organizational phenomena are modelable.
- ***Performance differential:*** It is possible to distinguish differences in organizational performance.
- ***Manipulability:*** Organization are entities that can be manipulated and transformed.
- ***Designability:*** Organizations are entities that can be designed. This is not to say that organizations do not evolve, nor that they cannot be found in nature, for assuredly both events occur. However, they can also be consciously designed and redesigned: organizational transformations can be purposeful and principled.

- ***Practicality:*** Organizational transformations (based on the design or manipulation of models) can be transferred into and implemented in actual practice.

- ***Pragmatism:*** The costs of modeling and researching organizations using computational methods are relatively lower than the costs of manipulating or researching similar aspects of actual organizations in vivo, and the benefits gained outweigh the costs.

Over time, these assumptions are becoming better defensible, and the degree of activity in COR circles is growing. COR provides a particularly effective venue for development of both theory and practice of organizations in MAS.

6 Conclusions

Thinking about organizations in MAS is an area of developing importance. Several perspectives have been presented, along with a comments on a number of basic themes and issues in multidisciplinary approaches to reasoning about organizations. In the short term, the most productive direction for research into organizations and MAS is likely to be that work that can be applied in the analysis, modeling, and simulation of organizations. Such work will have at least five benefits (cf. [Gasser, 2001b]):

- it will help advance the computational theory and conceptualization of organizations
- it will develop technical methods and infrastructure for implementing and experimenting with MAS organizations
- it will develop researchers' practice and experience with MAS organizations
- it will improve the pedagogical infrastructure and technology for MAS
- it will develop results on organizational models from human sciences, raising the impact of MAS research in the short term.

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