What is Coordination Theory?

Thomas W. Malone

Massachusetts Institute of Technology

SSM WP # 2051-88 February, 1988

Paper presented at the

National Science Foundation
Coordination Theory Workshop

Massachusetts Institute of Technology
Cambridge, Massachusetts

February 19, 1988

What is Coordination Theory?

The primary purpose of this paper is to stimulate discussion about a research agenda for a new interdisciplinary field. This field--the study of coordination--draws upon a variety of different disciplines including computer science, organization theory, management science, economics, and psychology. Work in this new area will include developing a body of scientific theory, which we will call "coordination theory," about how the activities of separate actors can be coordinated. One important use for coordination theory will be in developing and using computer and communication systems to help people coordinate their activities in new ways. We will call these systems "coordination technology."

Rationale

There are four reasons why work in this area is timely:

(1) In recent years, large numbers of people have acquired direct access to computers. These computers are now beginning to be connected to each other. Therefore, we now have, for the first time, an opportunity for vastly larger numbers of people to use computing and communications capabilities to help coordinate their work. For example, specialized new software has been developed to (a) support multiple authors working together on the same document, (b) help people display and manipulate information more effectively in face-to-face meetings, and (c) help people intelligently route and process electronic messages. It already appears likely that there will be commercially successful products of this new type (often called "computer supported cooperative work" or "groupware"), and to some observers these applications herald a paradigm shift in computer usage as significant as the earlier shifts to time-sharing and personal computing. It is less clear whether the continuing development of new computer applications in this area will depend solely on the intuitions of successful designers or whether it will also be guided by a coherent underlying theory of how people coordinate their activities now and how they might do so differently with computer support.

(2) In the long run, the dramatic improvements in the costs and capabilities of information technologies are changing--by orders of magnitude--the constraints on how certain kinds of communication and coordination can occur. At the same time, there is a pervasive feeling in American business that the pace of change is accelerating and that we need to create more flexible and adaptive organizations. Together, these changes may soon lead us across a threshhold where entirely new ways of organizing human activities become desirable. For

example, new capabilities for communicating information faster, less expensively, and more selectively may help create what some observers have called "adhocracies"--rapidly changing organizations with highly decentralized networks of shifting project teams. As another example, lowering the costs of coordination between firms may encourage more market transactions (i.e., more "buying" rather than "making") and, at the same time, closer coordination across firm boundaries (such as "just in time" inventory management). To understand and take advantage of these new possibilities will almost certainly require major extensions or reformulations of our current theories of organizations, of markets, and of management.

(3) Much recent activity in computer science has involved the exploration of a variety of parallel processing computer architectures. In many ways, physically connecting the processors to each other is easy compared to the difficulty of coordinating the activities of many different processors working on different aspects of the same problem. An intriguing possibility here is that lessons learned about how large groups of people coordinate their work can be applied to coordinating large groups of computer processors.

(4) Finally, in addition to these essentially practical applications, there appears to be a growing recognition of the commonality of theoretical problems in a variety of different disciplines that deal with the coordination of separate actors. For example, organization theorists and economists have found concepts about information processing useful in analyzing human coordination, and computer scientists have used economic and other social concepts in designing and analyzing parallel and distributed computer systems. In some cases, these cross-disciplinary connections offer the possibility of more precise analytical tools (e.g., computational models of human organizations or economic models of distributed computing). In other cases, they offer the possibility of rich new metaphors and concepts for analysis (e.g., "blackboard" models of information transfer in markets or "task forces" in distributed computing systems). One of the intriguing aspects of this interdisciplinary approach is the possibility of exploiting parallels between: (a) coordinating groups of people, (b) coordinating groups of computer processors or program modules, and (c) coordinating "hybrid" groups that include both people and computers.

For this enterprise to succeed, a great deal of cross-disciplinary interaction is needed. As Figure 1 suggests, abstract theories of coordination can apply to: (a) designing human organizations, (b) designing new technologies to help people coordinate their work, and (c) designing parallel and distributed processing computer systems. This is not, however, simply a matter of empirically studying human organizations to test theoretically motivated hypotheses, or using abstract theory to design new computer systems. We also expect that empirical insights or provocative new sytems will stimulate new theory, and that concepts from one domain will lead to applications in another (e.g., analogies between computer systems and human organizations). In each of these instances, the abstractions of coordination theory are the key intellectual links that facilitate such connections.

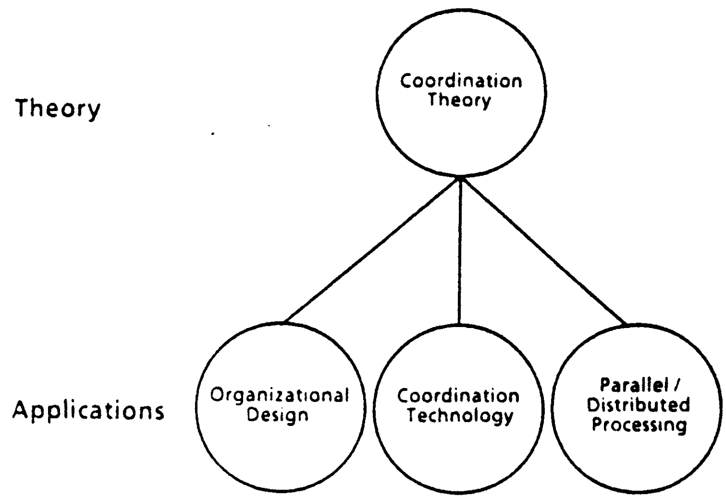

Figure 1
Coordination theory and applications

In the remainder of this paper, we will define what we mean by coordination theory and coordination technology, and then briefly suggest elements of a research agenda in this new area.

COORDINATION THEORY

What is coordination?

When multiple actors pursue goals together, they have to do things to organize themselves that a single actor pursuing the same goals would not have to do. We call these extra organizing activities *coordination*. More precisely, we define coordination as *the additional information processing performed when multiple, connected actors pursue goals that a single actor pursuing the same goals would not perform.*

Components of coordination. This definition of coordination implies the following components: (1) a set of (two or more) *actors*, (2) who perform *tasks*, (3) in order to achieve *goals* (cf. Malone, 1987; Malone & Smith, in press; Baligh & Damon, 1980; Baligh & Burton, 1981; Baligh, 1986). For example, an automobile manufacturing company might be thought of as having a set of goals (e.g., producing several different lines of automobiles) and a set of actors (people and machines) who perform the tasks that achieve these goals. As another example, a computer network can be thought of as having a set of goals (computations to be performed) and a set of computer processors of various types that perform the tasks that achieve these goals.

Coordination is in "the eye of the beholder." It is important to realize that the components of coordination are analytic concepts imposed by an observer. Thus, it is possible to analyze the same physical actions in different ways for different purposes. For instance, we might sometimes regard each person in a work group as a separate actor while at other times, we might regard the whole group as a single actor. Sometimes, we might even regard different parts of the brain of a single person as separate actors (e.g., Minsky, 1987).

Similarly, in order to analyze coordination, an observer must have some idea of what goal the activities help achieve. The actors themselves, however, may not all have the same goals or even have any explicit goals at all. For instance, in a market, we might regard the goal to be achieved as one of optimally allocating resources to maximize consumer utilities (e.g., Debreu, 1959). Even though no single individual has this goal, an observer might evaluate market coordination in terms of how well it achieved this goal.

Coordination is distinguished from production. Even if all three of the above components are present, not all activities in a situation are coordination. We divide the goal-relevant tasks into two categories: coordination tasks and production tasks. *Coordination tasks* are the information processing tasks that are performed because more than one actor is involved. *Production tasks* are all the other tasks that are performed in order to achieve the goals (e.g., Jonscher, 1982, 1983).

For instance, in a computer system solving a mathematical optimization problem using parallel processing, the mathematical computations that are necessary to solve the problem are the production tasks, while the other computing and communications activities--assigning and transmitting subparts of the problem to different processors--are the coordination tasks.

As another example, in an automobile manufacturing company, we can view the physical fabrication and assembly of automobiles as production tasks and all the other communication and decision-making necessary to produce automobiles as coordination tasks. In this sense, "coordination" is roughly synonymous with "management." Coordination, however, has several advantages as an analytic concept here. For instance: (1) it gives a powerful "analytic grip" by immediately implying components such as goals and multiple actors, and (2) it encompasses an intellectually coherent set of phenomena that appear in many domains (e.g., markets, committees, computers), not just hierarchical organizations.

What is coordination theory?

We define *coordination theory* as a body of principles about how the activities of separate actors can be coordinated. A test of the generality of a concept or principle is whether it can apply to more than one kind of actor. For instance, as the above examples suggest, at least some of the principles of coordination theory should be general enough to apply to a wide variety of different kinds of actors, including: organizations, individual people, computer processors, and parts of individual brains. We will focus our primary attention here on three kinds of groups: (1) groups of people, (2) groups of computer processors, and (3) groups that include both people and computers.

It seems likely that this kind of general theory of coordination can both draw upon, and contribute to, work in many different fields, including: economics, computer science, sociology, social psychology, linguistics, organization theory, and management information systems. Coordination theory will, therefore, be like other interdisciplinary fields that arise from the recognition of commonalities in problems that have previously been considered separately in a number of different fields.

For instance, as Figure 2 suggests, the field of cognitive science grew out of the recognition by researchers in several different fields (e.g., psychology, computer science, linguistics) that they were dealing separately with similar problems: how can information processing systems (people or computers) do things like use language, learn, plan, remember, and solve problems? (e.g., see Norman, 1980; Gardner, 1985). Progress in the new field has benefitted greatly from emergent cross-disciplinary connections, and the paradigms used have in turn been quite influential in the older fields (Gardner, 1985).

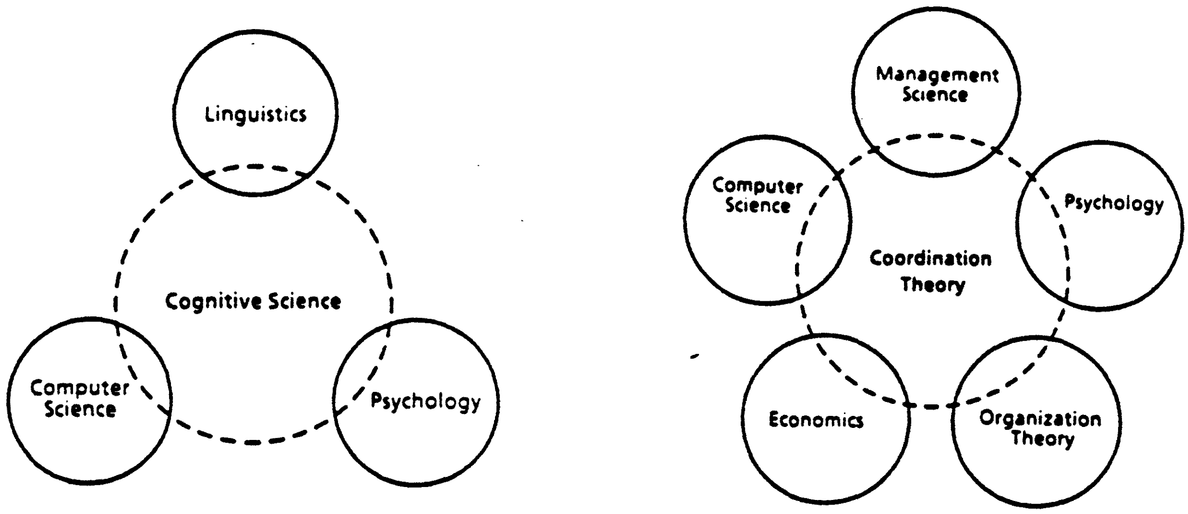

Figure 2
Both cognitive science and coordination theory
focus on problems previously considered separately in different fields.

In coordination theory (see Figure 2), the common problems have to do with coordination: How can overall goals be subdivided into tasks? How can tasks be assigned to groups or to individual actors? How can resources be allocated among different actors? How can information be shared among different actors to help achieve the overall goals? How can the different knowledge and conflicting preferences of different actors be combined to arrive at overall goals?

In fact, we can view coordination itself as another prototypical example of intelligent behavior, like learning, planning, and using language. Most previous work in cognitive science and artificial intelligence, however, has focused on intelligent behavior by individual actors. By shifting our focus to the coordination of multiple actors, new problems come into view. For instance: What forms of coordination allow a group of actors to perform more intelligently than any of its individual members? How can multiple actors jointly construct robust plans for their cooperative behavior? How can groups of actors coordinate joint decision-making? How can groups of actors learn new concepts?

Examples of coordination theory

To illustrate some of the possible connections between fields, Table 1 shows how selected research in two very different disciplines (economics and artificial intelligence) can be seen in terms of the disciplinary connections, and the paradigms used have in turn been quite influential in the older fields (Gardner, 1985).

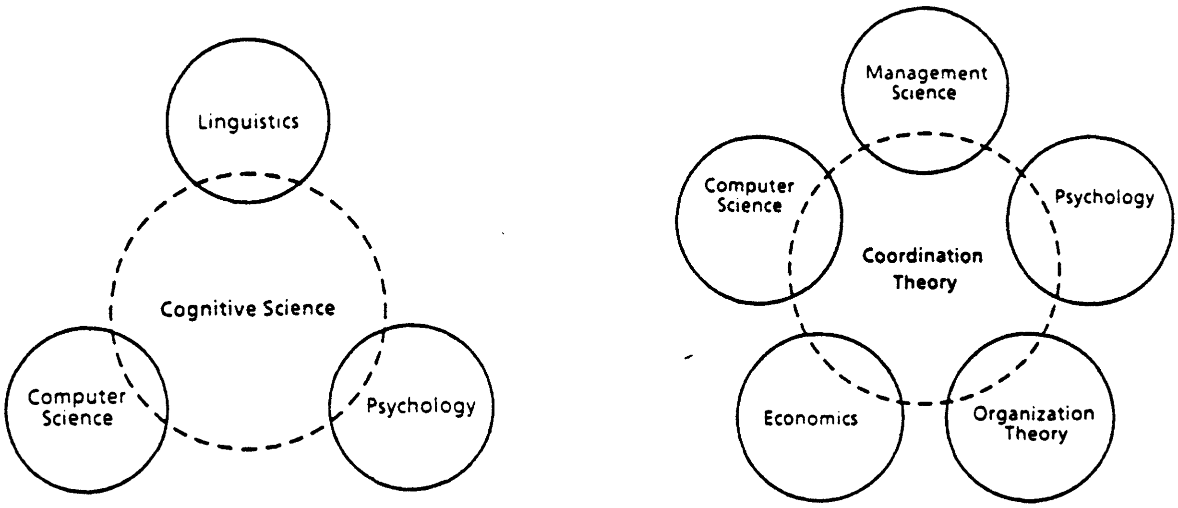

Figure 2
Both cognitive science and coordination theory
focus on problems previously considered separately in different fields.

In coordination theory (see Figure 2), the common problems have to do with coordination: How can overall goals be subdivided into tasks? How can tasks be assigned to groups or to individual actors? How can resources be allocated among different actors? How can information be shared among different actors to help achieve the overall goals? How can the different knowledge and conflicting preferences of different actors be combined to arrive at overall goals?

In fact, we can view coordination itself as another prototypical example of intelligent behavior, like learning, planning, and using language. Most previous work in cognitive science and artificial intelligence, however, has focused on intelligent behavior by individual actors. By shifting our focus to the coordination of multiple actors, new problems come into view. For instance: What forms of coordination allow a group of actors to perform more intelligently than any of its individual members? How can multiple actors jointly construct robust plans for their cooperative behavior? How can groups of actors coordinate joint decision-making? How can groups of actors learn new concepts?

Examples of coordination theory

To illustrate some of the possible connections between fields, Table 1 shows how selected research in two very different disciplines (economics and artificial intelligence) can be seen in terms of the concepts of coordination we have been discussing. Economists, for instance, have devoted a great deal of attention to mechanisms for allocating resources among actors. Artificial intelligence researchers, on the other hand, have paid more attention to ways of structuring information flows among actors. In both cases, benefits may result from combining these insights.

One insight suggested immediately by the table is the following: It has long been axiomatic in economics that markets are very efficient in their use of information because prices are the only pieces of information that need to be exchanged in order for resources to be allocated (e.g., Hayek, 1945). Recently, work in artificial intelligence has used the metaphor of a market (with contracts and bids) as the basis for assigning tasks to processors in a distributed computer network (Smith & Davis, 1981; Malone, Fikes, Grant, Howard, 1987; see also, Stankovic, 1985). These computer systems use prices to help allocate processing resources to tasks, but they also require that task descriptions (or product descriptions) be exchanged in order for these resource allocation decisions to be made. Looking at the analogy in this way makes obvious a restriction on the applicability of the conventional economic analysis of the problem: In markets where the products being exchanged are not standard, well-known commodities, not only prices, but also product descriptions need to be exchanged in order to efficiently allocate resources. The only markets in which only prices need to be exchanged are those in which the products being exchanged are all commodities, with descriptions that are well-known to all buyers and sellers. Thus, this work in computer science suggests an insight relevant to economics. Computer scientists may also be able to profit further from detailed economic analyses of different resource allocation schemes (e.g., Hurwicz, 1977; Reiter, 1986).

Economists may also find fertile new ground for analysis in the rich kinds of information sharing structures studied in artificial intelligence. For instance, in the "blackboard architecture" for designing artificial intelligence programs (Erman et al, 1980; Nii, 1986), the program contains a large number of "knowledge sources" or program modules that communicate with each other by placing the results of their computation on a "blackboard" where any other modules can examine them. In a system based on a more elaborate "scientific community metaphor" (Kornfeld & Hewitt, 1981), the different program modules post their results for other modules to use and also compete for computational resources from different "sponsors."

Other disciplines have also done work relevant to a general theory of coordination. For instance, several organization theorists have identified a tradeoff between coordination and "slack resources". Organizations with slack resources (such as large inventories or long product development times) can use them as a "cushion" to reduce the need for close coordination. Conversely, organizations that don't coordinate well pay a price in wasted resources (Nadler & Tushman, 1988, Galbraith, 1977; Thompson, 1967). Other organization theorists view coordination mechanisms as a means of dealing with external entities that control critical resources (Pfeffer, 1986, 1972; Van de Ven & Walker, 1984; Pennings, 1980). For instance, mergers and acquisitions can absorb critical resources, while interlocking boards of directors can co-opt powerful outside interests. One test of the generality of these theories is the observation that they can apply at several levels. For instance, they apply not only to inter-firm coordination, but also to coordination between teams within a firm (e.g., engineering teams that include representatives of outside interests such as marketing; see Ancona & Caldwell, 1987).

An extended example of coordination theory and its application

To illustrate some of these points more concretely, we describe in this section an example of how concepts about coordination can be transported across disciplinary boundaries. In this example, the design and analysis of distributed computer systems eventually led to abstract theories about coordination that helped predict how human organizations might change with the widespread use of information technology.

Distributed computer systems

Our example begins with the "contract nets" computer system mentioned above (Smith & Davis, 1981; Davis & Smith, 1983), developed by researchers working primarily in artificial intelligence. It draws on common-sense economic knowledge about how markets for competitive bidding contracts typically work. The system formalizes this knowledge as a sequence of messages to be exchanged by computer processors sharing tasks in a network. In this system, the "contracts" are arbitrary computational tasks that can potentially be performed by any of a number of processors on the network, the "clients" are machines at which these tasks originate, and the "contractors" are machines that might process the tasks.

In order to assign tasks to processors in this system, a client first broadcasts an *announcement* message to all potential contractors. This message includes a description of the task to be performed and the qualifications required of potential contractors. The potential contractors then use this information to decide whether to submit a *bid* on the task. If they decide to bid, their bid message includes a description of their qualifications and their availability for performing the task. The client uses these bid messages to decide which contractor should perform the task and then sends an *award* message to notify the contractor that has been selected. Finally, the contractor returns a *result* message containing the results of the computational task it has performed. One of the desirable features of this system is its great degree of decentralization and the flexibility it provides for how both clients and contractors can make their decisions. For instance, clients may select contractors on the basis of estimated completion time or the presence of specialized data; contractors may select tasks to bid on based on the size of the task or how long the task has been waiting.

Based on these ideas, a later system (called Enterprise) was developed to allow personal workstations connected by a local area network to share tasks (Malone, Fikes, Grant, & Howard, 1987, in press). In this way, for instance, users can take advantage of the unused processing capacity at idle personal workstations elsewhere on the network.

In the course of designing this system, we realized that there were several different possible configurations for it and that these alternative configurations were analogous to different forms of human organizations. For example, one plausible alternative to having announcement messages broadcast to all potential contractors would be to have "broker" machines on the network that (1) received announcements of new tasks to be done, (2) kept track of the capabilities and availability of contractors, and (3) assigned tasks to available contractors based on priorities and estimated completion times. This scheme, unlike the original "decentralized market" is analogous to a kind of "centralized market." If there are different "brokers" for each different type of contractor (e.g., a broker for printers, a broker for high speed arithmetic processors, etc.), then this scheme is loosely analogous to a "functional hierarchy" in a human organization, where there are separate departments for each kind of task (e.g., marketing, engineering, and manufacturing) with each department having a manager who is responsible for assigning tasks to different groups or individuals. Finally, if the machines do not share tasks over the network at all, but instead each machine has its own facilities for tasks such as printing and arithmetic processing, then this is loosely analogous to a "product hierarchy" in human organizations in which each product division has its own separate groups for marketing, manufacturing, engineering, and so forth.

As we will see in the next subsection, these rough analogies suggest a new way of thinking about alternative ways of coordinating the assignment of tasks to actors.

Analysis of tradeoffs in alternative coordination structures

The next step in our example is the formalization of these intuitions about alternative coordination structures. In a series of papers (Malone, 1987; Malone & Smith, in press), we developed formal models to represent: product hierarchies, functional hierarchies, centralized markets, and decentralized markets. Then we analyzed tradeoffs among these structures in terms of production costs, coordination costs, and vulnerability costs. These models are unusual in that they include detailed definitions of the structures at a micro-level and mathematical derivations of comparisons among them at a macro-level. The mathematical derivations use models of task processing based on queueing theory and probability theory. The derivations also include assumptions about the number of messages that are exchanged in assigning tasks to actors. These assumptions are based on a generalization of the task assignment process used in the distributed computing systems described above (e.g., announcement, bid, award, and result).

Clearly there are many important aspects of human organizations and computer systems that are not captured by these simple quantitative models of coordination structures. In many cases, especially in human organizations, these "non-quantitative" factors are more important than the simple factors modeled here. Nevertheless, the simple models help illuminate a surprisingly wide range of phenomena. For instance, the models are consistent with a number of previous theories about organizational design (e.g., March & Simon, 1958; Galbraith, 1973; Williamson, 1981) and with major historical changes in the organizational forms of both human organizations (Chandler, 1962, 1977) and computer systems. They help analyze design alternatives for distributed scheduling systems, and they suggest ways of analyzing the structural changes associated with introducing new information technology into organizations (Crowston, Malone, & Lin, 1987; Malone & Smith, in press). In the next subsection, we describe some general insights that result from this last use of the models.

Application to predicting effects of information technology on organizational structures

One of the simple insights contained in the models is that coordination is itself an activity that has costs and benefits. Even though there are many other forces that may affect the way coordination is performed in organizations and markets (e.g., global competition, government regulation, interest rates), one important factor is clearly its cost. Furthermore, it seems quite plausible to assume that information technology is likely to significantly reduce the costs of certain kinds of coordination (e.g., Crawford, 1982).

Now, using some elementary ideas from microeconomics about substitution and elasticity of demand, we can make some simple predictions about the possible effects of reducing coordination costs. It is useful to illustrate these effects by analogy with similar changes in the costs of transportation induced by the introduction of trains and automobiles:

(1) A "first order" effect of reducing transportation costs with trains and automobiles was simply some substitution of the new transportation technologies for the old: people began to ride on trains more and in horse-drawn carriages less.

(2) A "second order" effect of reducing transportation costs was to increase the amount of transportation used: people began to travel more when this could be done more cheaply and conveniently in trains than on foot.

(3) Finally, a "third order" effect was to allow the creation of more "transportation-intensive" structures: people eventually began to live in distant suburbs and use shopping malls--both examples of new structures that depended on the widespread availability of cheap and convenient transportation.

Similarly, we can expect several effects from using new information technologies to reduce the costs of coordination:

(1) A "first order" effect of reducing coordination costs with information technology may be to substitute information technology for some human coordination. For instance, it has long been commonplace to predict that computers will lead to the demise of middle management because the communication tasks performed by middle managers could be performed less expensively by computers (e.g., Leavitt & Whisler, 1958). In fact, this prediction has not yet been fulfilled, perhaps, in part, because of the following second and third order effects.

(2) A "second order" effect of reducing coordination costs may be to increase the overall amount of coordination used. In some cases, this may overwhelm the first order effect. For instance, in one case we studied, a computer conferencing system was used to help remove a layer of middle managers (see Crowston, Malone, & Lin, 1987). Several years later, however, almost the same number of new positions (for different people at the same grade level) had been created for staff specialists in the corporate staff group, many of whom were helping to develop new computer systems. One interpretation of this outcome is that the managerial resources no longer needed for simple communication tasks could now be applied to more complex analysis tasks that would not previously have been undertaken.

(3) A "third order" effect of reducing coordination costs may be to encourage a shift toward the use of more "coordination-intensive" structures. For instance, the following speculative examples suggest some possibilities:

(a) *More adaptive organizations*. We have already mentioned how rapid technological change and global interdependencies are creating increasingly turbulent environments to which organizations must adapt. It is clear that new information technologies--like many previous communication technologies (such as telephone, television, and the printing press)--have the potential to help this problem by transfering information more rapidly and less expensively. Unlike previous communication technologies, however, the new computer-based technologies also have the potential to transfer information *more selectively*. Thus, as we will see in the next section, new coordination technologies have the potential to help reduce information overload by directing information more accurately to people who want to know it without overloading others. Ultimately, these new coordination technologies may help speed up the "information metabolism" of organizations--the speed with which organizations can take in information, move it around, digest it, and respond to it.

(b) *More adhocracies*. Another possibility suggested by some of our models (Malone & Smith, in press) is that the widespread use of information technology can facilitate what some observers (e.g., Mintzberg, 1979; Toffler, 1970) have called "adhocracies." Adhocracies are rapidly changing organizations with shifting project teams, often highly decentralized networks of autonomous entrepeneurial groups. Electronic media, such as electronic mail, computer conferencing, and electronic bulletin boards, may help bring together and then coordinate the people with diverse knowledge and skills that are needed for these teams.

(c) *More use of markets*. A final possibility suggested by our models (Malone, Yates, & Benjamin, 1987) is that by reducing the costs of coordination, information technology may lead to an overall shift toward proportionately more use of markets--rather than internal decisions within firms--to coordinate economic activity. Since, market transactions may often have higher coordination costs than internal coordination (Williamson, 1981; Malone, 1987), an overall reduction in the "unit costs" of coordination should reduce the importance of the dimension on which markets have a disadvantage. This, in turn, should lead to markets becoming more desirable in situations where internal transactions were previously favored and thus to (i) more "buying" rather than "making", (ii) less vertical integration, and (iii) smaller firms. These theoretically motivated predictions are, of course, testable hypotheses, and one item on the research agenda of this new area could be to empirically test whether the predictions are already coming true.

As these last examples suggest, one of the most intriguing questions that coordination theory may help answer is what new kinds of coordination structures will be desirable in the electronically connected world of the near future. What are the organizational equivalents of suburbs and shopping malls that information technology may make possible? Which of these new possibilities are likely to be satisfying places to work and which ones aren't? To understand these new possibilities will require major extensions or reformulations of our current theories of organizations, markets, and management. The coordination theory perspective we have described seems likely to be able to contribute significantly to this endeavor.

Lessons from this example

We have seen in the above example how the development of abstract coordination theory can be stimulated by and applied to different kinds of empirical examples--both those involving computer systems and those involving human organizations. We hope that further work in this interdisciplinary area will encourage more of this kind of extended interdisciplinary interaction.

COORDINATION TECHNOLOGY

As the very name "computer" suggests, we usually think of computers as machines for "computing" things--that is, for taking in information, performing calculations or other manipulations on it, and then putting out the results of these calculations. This kind of "computing" is essentially a solitary activity, and many of the most widespread uses of personal computers today focus on supporting individuals, working alone, on tasks like spreadsheet analysis and word processing.

Now, however, computers are beginning to be connected to each other with more and more extensive forms of telecommunications technology. Therefore, we now have, for the first time, an opportunity to use combinations of computing and communications technologies in new ways. We suspect that one of the most important uses of these new systems in the next few decades will be to help groups of people coordinate their activities.

In fact, from this perspective it becomes clear that many of the existing uses of computers for tasks such as accounting, are actually ways of helping large groups of people coordinate their activities. In short, we suspect that computers in the next few decades may well be remembered, not as a technology used primarily to "compute" things, but as a technology used primarily to "coordinate" things--that is, as "coordination technology."

The need to help design new kinds of coordination techology may also be one of the primary driving forces behind--and one of the primary applications for--the development of coordination theory.

What is coordination technology?

We define *coordination technology* as any use of technology, especially computer and communications technology, to help people coordinate their activities.[1] This term seems to succinctly capture the concepts implied by a number of other terms used recently in both academic and popular writing such as "computer-supported cooperative work," "groupware," "computer-supported groups," and "interpersonal computing" (see, for example, Proceedings of Conference on Computer-Supported Cooperative Work, 1986; Olson, in press; Johansen, 1987; Curtis & Malone, 1987; Greif, in press; Richman, 1987).

For example, we intend coordination technology to include the support of cooperative activities such as multiple authors collaborating on the same document (Broderbund, 1986; Trigg, Suchman & Halasz, 1986) and information sharing via electronic mail and computer conferencing (Malone, Grant, Turbak, Brobst, & Cohen, 1987; Hiltz & Turoff, 1978; Sproull & Kiesler, 1986). But we also intend coordination technology to include support for activities where competition or other conflicts of interest are paramount such as market transactions (Malone, Yates, & Benjamin, 1987), negotiation (Nyhart & Goeltner, 1987), and debate (Lowe, 1985).

Coordination technology may include tools to help display, manipulate, and route information in meetings, either face-to-face meetings (e.g., Stefik, Foster, Bobrow, Kahn, Lanning, & Suchman, 1987; Applegate, Konsynski,& Nunamaker, 1986, Kraemer & King, 1986; DeSanctis & Gallupe, 1987) or meetings of people at a distance from each other (e.g., Sarin & Greif, 1985).

Coordination technology also includes many kinds of delayed communication for tasks such as tracking commitments people have made to each other (Winograd & Flores, 1986), project management (Sluizer & Cashman, 1984), and meeting scheduling (e.g., Malone, Grant, Lai, Rao, & Rosenblitt, 1987). Clearly many different kinds of media can be used in coordination technology including video (e.g., Goodman & Abel, 1986), audio, graphics, and text.

In addition to these recent examples of using technology in new ways to support non-routine group tasks (such as writing, decision-making, and project management), coordination technology also includes support for highly routine kinds of coordination transactions (such as the order entry, inventory control and other accounting tasks often performed by traditional mainframe computers). While many of these traditional systems are well understood and not of great research interest, a better understanding of coordination may lead us to rethink old transaction systems by, for instance, integrating them with electronic messaging systems for handling non-routine cases (Fikes & Henderson, 1980; Malone, Grant, Lai, Rao, & Rosenblitt, 1987b), or extending them across firm boundaries (e.g., Cash & Konsynski, 1985; Malone, Yates, & Benjamin, 1987).

One way of categorizing these different coordination technologies is in terms of the characteristics of their communication such as: *time* (simultaneous vs. delayed), *location* (face-to-face vs. distant), and *medium* (video, audio, graphics, text, structured data). We believe a more useful taxonomy of coordination technologies will result from a characterization of different *task types* which such systems can support (e.g., designing, authoring, scheduling, decision-making, budgeting, planning, project management, buying, selling, negotiating), and other *task characteristics* (e.g., routine vs. non-routine).

Part of the research agenda of this new field is to develop a principled taxonomy of the kinds of coordination involved in tasks like these and generative theories about how technology can support them. This goal is a clear example of the connection between coordination theory and coordination technology.

Extended example of coordination technology

To illustrate more concretely some of the possibilities for innovative kinds of coordination technology, we will describe in more detail a system called the Information Lens. This system was designed, using ideas from artificial intelligence, to help people share information and coordinate their activities (see Malone, Grant, Turbak, Brobst, & Cohen, 1987; Malone, Grant, Lai, Rao, & Rosenblitt, 1987)

Information sharing

We define the information sharing problem as one of disseminating information to the actors who will find it useful without distracting others who will find no value in its contents. Part of the initial motivation for the Information Lens system came from an abstract coordination theory analysis of the importance of this problem in creating flexible and adaptive organizations--whether of people or of computers (see Malone, in press).

There are also, however, more immediate practical reasons to believe that this problem is likely to become increasingly important as it becomes both technically and economically feasible for people to send electronic messages and other documents to large numbers of possible recipients. First, it is already a common experience in mature computer-based messaging communities for people to feel flooded with large quantities of electronic "junk mail" (e.g., Denning, 1982; Hiltz & Turoff, 1985). At the same time, it is also a common experience for people to be ignorant of facts that would facilitate their work and that are known elsewhere in their organization. The Information Lens helps people solve both these problems: it helps people filter, sort, and prioritize messages that are already addressed to them, and it also helps them find useful messages they would not otherwise have received. Possible applications of systems like this include: (a) helping top managers and their staff discover patterns in the intelligence reports they receive from the field, (b) helping to route engineering change notices to appropriate people in different engineering, manufacturing, and other groups, and (c) helping to quickly find, in a large organization, the people who know the answers to specialized questions.

A key idea in the Information Lens is that semi-structured message templates can simplify both the original composition of messages and their subsequent processing. For example, meeting announcements can be structured as templates that include fields for "date", "time", "place", "organizer", and "topic", as well as any additional unstructured information.

More specifically, the Lens system enhances the usual capabilities of an electronic mail system with four important optional capabilities: (1) Senders can conveniently compose their messages using structured templates that suggest the kinds of information to be included in the message and likely alternatives for each kind of information; (2) Receivers can conveniently specify rules to automatically filter and classify their incoming messages into folders based on the same dimensions used by senders in constructing messages; (3) Senders can include as an addressee of a message, in addition to specific individuals or distribution lists, a special mailbox (currently named "Anyone") to indicate that the sender is willing to have this message automatically redistributed to anyone else who might be interested; and (4) Receivers can specify rules that find and show messages addressed to "Anyone" that the receiver would not otherwise have seen.

Messages that include "Anyone" as an addressee are delivered to the explicit addressees as well as to any additional recipients whose rules select them. Messages can thus be selectively disseminated only to people who are likely to be interested in them. This framework supports many kinds of information sharing in addition to straightforward electronic mail. For example, we have recently begun receiving a daily on-line feed of *New York Times* articles which already contain fields such as subject, priority, and author. The users of our system can now specify rules based on these fields for selecting and sorting news articles just like their rules for sorting any other kind of message.

Other coordination applications

We have been surprised to find that these semi-structured messages are useful, not only for the original information sharing application, but also for supporting a variety of other coordination processes in organizations (see Malone, Grant, Lai, Rao, & Rosenblitt, 1987). For example, when the system knows the types of messages it is receiving, it can (1) take automatic actions on receiving certain kinds of messages, and (2) suggest actions that its human users might take on receiving other kinds of messages. Simple examples of using these capabilities include (1) setting up rules to automatically forward meeting requests to a secretary who keeps a calendar, and (2) having the system automatically present its users an option of loading the files specified in "bug fix announcements." We have also recently used these ideas to implement larger scale demonstration systems that help people schedule meetings, engage in "computer conferences", and keep track of tasks they have agreed to do. For instance, simply by creating several new types of messages (e.g., "meeting proposal" and "meeting acceptance") and by adding several new kinds of rule actions and response options (e.g., "accept meeting", "add to calendar"), we created a system specifically designed to help people schedule meetings.

RESEARCH AGENDA

In this section, we will present a very preliminary sketch of a research agenda for this new area.

Methodologies

One way of characterizing prospective research projects is in terms of their primary methodologies:

(1) *Empirical studies of human coordination.* This category can include a variety of empirical methodologies, such as:

(a) ethnographic field observations of organizational coordination processes,

(b) laboratory experiments with group problem-solving, and

(c) econometric studies of firms and markets as coordination mechanisms.

These studies can be used both to stimulate the development of new theory (e.g., a taxonomy of coordination processes) and to test existing theories (e.g., the prediction that reducing coordination cost should lead to a greater proportion of market coordination).

(2) *Design of new technologies for supporting human coordination.* This category includes designing new computer and communications systems to support a wide variety of kinds of coordination tasks at different levels of generality: writing, design, project management, meetings, decision-making, etc. In some cases, the design of such systems will embody and make more concrete a prior theory; in other cases, a good idea for system design will stimulate new theory.

(3) *Design and experimentation with new methods for coordinating distributed and parallel processing computer systems.* This category includes experimentation with different methods for solving the coordination problems that arise in distributed and parallel computer systems such as synchronization, and task assignment. Again, such experiments may, in some cases apply previous theories, and in other cases help generate new theories.

(4) *Formal representation and analysis of coordination processes.* This category can include at least two kinds of formal modeling:

(a) mathematical modeling. Much of the work in economics falls in this category.

(c) computer simulations. It may also be useful, in some cases, to use knowledge representation techniques (such as ideas about inheritance and production rules) as a theoretical language without actually running simulations.

Questions

Another way of characterizing prospective research in this area is in terms of the kinds of questions it might answer. For instance, the following questions suggest some important general issues that transcend individual disciplines:

(1) What are the alternative methods for allocating scarce resources to goals and what are the relative advantages and disadvantages of these different methods in different situations?

(a) In what ways is the assignment of actors to tasks different from and similar to the more general allocation of resources to goals?

(b) How can a group of actors select a goal to pursue?

(c) How does the presence of significant conflicts of interest among actors affect the desirability of different resource allocation methods?

(d) How do different kinds of information processing limitations of actors affect the desirability of different methods? For example, are some methods appropriate for coordinating people that would not be appropriate for coordinating computer processors, and vice versa? What new methods for coordinating people become desirable when human information processing capacities are augmented by computers?

(2) What are the alternative methods for planning a sequence of interdependent actions by different actors and what are their relative advantages and disadvantages?

(3) How general are coordination processes?

(a) Are there a number "generic coordination processes" that are found in very many situations? If so, what are they? For example, are there general heuristics for coordination that are analogous to the general problem-solving heuristics studied in cognitive science and artificial inteligence?

(b) To what extent does the ability to coordinate well depend on general knowledge about coordination as opposed to specific knowledge about particular tasks and situations?

CONCLUSIONS

Clearly the questions we have just listed are only the beginning of a set of research issues in the interdisciplinary study of coordination. However, we believe they illustrate how the notion of "coordination" provides a set of abstractions that help unify questions previously considered separately in a variety of different disciplines.

While much work remains to be done, it appears that this approach can build upon much previous work in these different disciplines to help solve a variety of immediate practical needs, including: (1) designing computer and communication tools that enable people to work together more effectively, (2) harnessing the power of multiple computer processors working simultaneously on related problems, and (3) creating more flexible and more satisfying ways of organizing collective human activity.

ACKNOWLEDGEMENTS

Much of this paper appeared as part of a proposal submitted to the National Science Foundation. I am especially grateful to Deborah Ancona, John Carroll, Randall Davis, and John Little for comments on earlier versions of the paper.

FOOTNOTE

1 The term "coordination technology" has been used previously by Harry Stevens and Anatol Holt.

Table 1
Coordination in Selected Research Areas

Area	Agents	Actions	Information Exchanged	Goal	Important Issues	References
Economics						
classical micro-economics	firms and consumers	choosing prices and quantities for various commodities	prices	optimal distribution of resources	determining optimal resource allocation	Debreu, 1959
team theory	individual decision-makers	setting values of decision variables	values of variables	maximizing team utility	determining optimal rules for decision making and information sharing	Marschak & Radner, 1972
agency theory	principals and agents	agent acts; principal monitors and rewards.	incentives, measures of outcomes and/or behavior	maximize utility of outcomes	determining optimal incentive structures	Ross, 1973; Holmstrom, 1979; Jensen & Meckling, 1976
Artificial Intelligence						
blackboard models	computational "knowledge sources"	compute consequences of available information	hypotheses on "blackboard"	solve problem	dividing knowledge; representing shared information; allocating processing time	Erman et al, 1980; Nii, 1986
scientific community metaphor	sprites	compute consequences of available information	assertions	solve problem	allocating processing time among agents	Kornfeld & Hewitt, 1981
contract nets	clients and contractors	arbitrary computation	announcements, bids, awards and results	solve multiple problems	allocating tasks to agents	Smith & Davis, 1981

COORDINATION TECHNOLOGY

As the very name "computer" suggests, we usually think of computers as machines for "computing" things--that is, for taking in information, performing calculations or other manipulations on it, and then putting out the results of these calculations. This kind of "computing" is essentially a solitary activity, and many of the most widespread uses of personal computers today focus on supporting individuals, working alone, on tasks like spreadsheet analysis and word processing.

Now, however, computers are beginning to be connected to each other with more and more extensive forms of telecommunications technology. Therefore, we now have, for the first time, an opportunity to use combinations of computing and communications technologies in new ways. We suspect that one of the most important uses of these new systems in the next few decades will be to help groups of people coordinate their activities.

In fact, from this perspective it becomes clear that many of the existing uses of computers for tasks such as accounting, are actually ways of helping large groups of people coordinate their activities. In short, we suspect that computers in the next few decades may well be remembered, not as a technology used primarily to "compute" things, but as a technology used primarily to "coordinate" things--that is, as "coordination technology."

The need to help design new kinds of coordination techology may also be one of the primary driving forces behind--and one of the primary applications for--the development of coordination theory.

What is coordination technology?

We define *coordination technology* as any use of technology, especially computer and communications technology, to help people coordinate their activities.[1] This term seems to succinctly capture the concepts implied by a number of other terms used recently in both academic and popular writing such as "computer-supported cooperative work," "groupware," "computer-supported groups," and "interpersonal computing" (see, for example, Proceedings of Conference on Computer-Supported Cooperative Work, 1986; Olson, in press; Johansen, 1987; Curtis & Malone, 1987; Greif, in press; Richman, 1987).

For example, we intend coordination technology to include the support of cooperative activities such as multiple authors collaborating on the same document (Broderbund, 1986; Trigg, Suchman & Halasz, 1986) and information sharing via electronic mail and computer conferencing (Malone, Grant, Turbak, Brobst, & Cohen, 1987; Hiltz & Turoff, 1978; Sproull & Kiesler, 1986). But we also

FOOTNOTE

1 The term "coordination technology" has been used previously by Harry Stevens and Anatol Holt.

BIBLIOGRAPHY

Applegate, L. M., Konsynski, B. R., & Nunamaker, J. F. A group decision support system for idea generation and issue analysis in organizational planning. *Proceedings of the Conference on Computer-Supported Cooperative Work*, Austin, Texas, December 3-5, 1986.

Arrow, K. *The limits of organization*. New York: Norton, 1974.

Arrow, K.J. and Hurwicz, L. *Studies in resource allocation processes*. Cambridge, England: Cambridge University Press, 1977.

Astley, W.M. and Van de Ven, A.H. Central perspectives and debates in organization theory. *Administrative Science Quarterly*, 1983, *28*, 245-273.

Attewell, P. & Rule, J. What we know and what we don't know. *Communications of the ACM*, 1984 (Dec.), 1184-92.

Axelrod, R. *The evolution of cooperation*. New York: Basic Books, 1984.

Baligh, H. H. Decision rules and transactions, organizations and markets, *Management Science*, 1986, *32*, 1480-1491.

Baligh, H. H. & Burton, R. M. Describing and designing organizational structures and processes. *International Journal of Policy Analysis and Information Systems*, 1981, *5*, 251-266.

Baligh, H. H. & Burton, R. M. The process of designing organization structures and their information substructures. In S. K. Chang (Ed.), *Management and office Information systems*. New York: Plenum Press, 1984, pp. 3-26.

Baligh, H.H., Burton, R., and Obel, B. Designing organizational structures: An expert system method. *Economics and Artificial Intelligence Conference*, Aix-en-Provence, France, September 1986; and the *Meeting of ORSA/TIMS*, Miami FL, October 1986.

Baligh, H. H. & Damon, W. W. Foundations for a systematic process of organization structure design. *Journal of Information and Optimization Sciences*, 1980, *1*, 133-165.

Baligh, H. H. & Richartz, L. *Vertical market structures*. Boston: Allyn and Bacon, 1967.

Begeman, M., Cook, P., Ellis, C., Graf, M., Rein, G., & Smith, T., Project NICK: Meetings augmentation and analysis. *Proceedings of the Conference on Computer-Supported Cooperative Work*, Austin, Texas, December 3-5, 1986.

Booker, L.B., Goldberg, D.E., and Holland, J.H. Classifier systems and genetic algorithms. Photocopy of pre-publication draft, May 27, 1987.

Broderbund Software, Inc. *For comment*, (computer software), San Rafael, CA, 1986.

Burton, R. M. & Obel, B. *Designing efficient organizations: Modelling and experimentation*. Amsterdam: Elsevier Science Publishers B.V., 1984.

Burton, R., and Obel, B. Opportunism, incentives, and the M-form hypothesis: A laboratory study. Photocopy of paper presented at the MIT *Workshop on Organizational Science*, N. Andover, MA., June 10-12, 1987.

Cash, J. I., & Konsynski, B. R. IS redraws competitive boundaries, *Harvard Business Review*, March-April 1985, *63*, pp. 134-142.

Chandler, A. D. *The visible hand: The managerial revolution in American business*. Cambridge, Mass.: Belknap Press, 1977.

Chandler, A. D. *Strategy and structure*. New York: Doubleday, 1962.

Coase, R. H. The nature of the firm. *Economica N. S.*, 1937.

Cohen, M.D. Artificial intelligence and the dynamic performance of organizational designs. In F. G. March & R. Weissinger-Baylon (Eds.), *Ambiguity and command: Organizational perspective on military decision making*. Marshfield, MA: Pitman Publishing, Inc., 1986.

Cohen, M.D. The power of parallel thinking. *Journal of Economic Behavior and Organization*. 1982, *2*, 1-22.

Cohen, M., March, J., and Olsen, J. A garbage can model of organizational choice. *Administrative Science Quarterly*, 1972, *17*, 1-25.

Crawford, A.B., Corporate electronic mail: A communicaation-intensive applicaion of information technology, *MIS Quarterly*, 1982 (Sept.), 1-13.

Crowston, K., Malone, T. W., & Lin, F. Cognitive science and organizational design: A case study of computer conferencing, *Human-Computer Interaction*, 1987, *3*, 59-85.

Cyert, R.M. and March, J.G. *Behavioral theory of the firm*. Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1963.

Davis, R. A model for planning in a multi-agent environment: Steps toward principles for teamwork. MIT AI Working Paper 217, June 1981.

Davis R., Buchanan, B. & Shortliffe, E. Rules as a representation in knowledge-based consultation systems. *Artificial Intelligence*, 1977 (Feb.), 15-47.

Davis, R. & Smith, R. G. Negotiation as a metaphor for distributed problem solving. *Artificial Intelligence*, 1983, *20.*, 63-109.

Debreu, G. *Theory of value: An axiomatic analysis of economic equilibrium*. New York: Wiley, 1959.

Denning, P. Electronic junk. *Communications of the ACM, (1982)*, *23*, 3, 163-165.

DiMaggio, P.J. & Powell, W.W. The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review*, 1983, *48*, 147-160.

Durfee, E.H. and Lesser, V.R. Using partial global plans to coordinate distributed problem solvers. U. Mass. Amherst, COINS Technical Report 87-06, January 1987.

Durfee, E.H., Lesser, V.R., and Corkill, D.D. Coherent cooperation among communicating problem solvers. U. Mass. Amherst, COINS Technical Report 85-15, September 30, 1985.

Erman, L.D., Hayes-Roth, F., Lesser, V.R. and Reddy, D.R. The Hearsay-II Speech Understanding System:Integrating knowledge to resolve uncertainty. *Computing Surveys*, 1980, *12*, 213-253.

Farber, D. J. and Larson, K. C. The structure of the distributed computing system--Software. In J. Fox (Ed.), *Proceedings of the Symposium on Computer-Communications Networks and Teletraffic*, Brooklyn, NY: Polytechnic Press, 1972, pp. 539-545.

Farrell, J. & Saloner, G. Coordination through committees and markets. Hoover Institution Working Papers in Economics E-87-25, Stanford University, Stanford, CA, June, 1987.

Farrell, J. & Saloner, G. Installed base and compatibility: Innovation, product preannouncements, and predation. *American Economic Review*, 1986, *76*, 940-955.

Farrell, J. & Saloner, G. Standardization, compatibility, and innovation. *Rand Journal of Economics*. 1985, *16*, 70-83.

Fikes, R.E. & Henderson, A. On supporting the use of procedures in office work. *Proceedings of the First Annual National Conference on Artificial Intelligence*, 1980. (pp. 202-207). Stanford University, Stanford, California.

Fischoff, B. Judgment and decision making. In Sternberg and Smith (Eds.), *The Psychology of Human Thought*. New York: Wiley, 1986.

Fox, M.S. An organizational view of distributed systems. *IEEE Transactions on Systems, Man, and Cybernetics*, 1981, *SMC-11*, 70-79.

Galbraith, J. *Designing complex organizations*. Reading, MA: Addison-Wesley, 1973.

Galbraith, J. *Organization design*. Reading, Mass.: Addison-Wesley, 1977.

Gardner, D. *The mind's new science: A history of the cognitive revolution*. New York: Basic Books, 1985.

Genesereth, M. R., Ginsberg, M. L. & Rosenschein, J. S. Cooperation without communication. *Proceedings of the Fifth National Conference on Artificial Intelligence*, Philadelphia, PA, August 11-15, 1986.

Grossman, S. & Hart, O. An analysis of the principal-agent problem. *Econometrica*, 1983, *51*, 7-45.

Gulick, L. & Urwick, L. (Eds.) *Papers on the science of administration*. New York: Institute of Public Administration, Columbia University, 1937.

Gupta, A. (Ed.) *Multi-microprocessors*. New York: IEEE Press, 1987, 23-69.

Gupta, A. & Toong, H.D. Increasing throughput of multiprocessor configurations. *IEEE Transactions on Industrial Electronics*, 1985, *IE-32*, 3.

Halasz, F., Moran, T., & Trigg, R. Notecards in a nutshell. *Proceedings of the Conference on Computer Human Interaction (CHI '87)*, Toronto, Canada, April, 7-9, 1987.

Hammon, K. et al. Social judgment theory: Applications in policy formation. In Kaplan and Schwartz (Eds.), *Human judgment and decision processes in applied settings.* New York: Academic Press, 1977.

Hannan, M.T. & Freeman, J. The population ecology of organizations. *American Journal of Sociology*, 1977, *82*, 929-966.

Hastie, R., Penrod, S. & Pennington, N. *Inside the jury.* Cambridge, Massachusetts: Harvard University Press, 1983.

Hayek, F. The uses of knowledge in society. *American Economic Review*, 1945 (Sept.), *35*, 519-530.

Hewitt, C. Offices are open systems. *ACM Transactions on Office Information Systems*, 1986 (July), *4*, 3, 271-287.

Hillis, D. *The connection machine.* Cambridge, MA: MIT Press, 1985.

Hiltz, S. R. and Turoff, M. *The network nation: Human communication via computer.* Reading, Massachusetts: Addison-Wesley, 1978.

Holmstrom, B. Moral hazard and observability. *The Bell Journal of Economics*, 1979 (Spring), *10*, 74-91.

Huber, G. P. The nature and design of post-industrial organizations. *Management Science, 30*, 8 1984 (August), 928-951.

Huberman, B. A. (Ed.). *The ecology of computation*, Amsterdam: North Holland, in press.

Hurwicz, L. The design of resource allocation mechanisms. *American Economic Review Papers and Proceedings*, *58*, 1973 (May), 1-30. Reprinted in Arrow and Hurwicz (Eds), *Studies in resource Allocation Processes*, Cambridge, England: Cambridge University Press, 1977.

Jonscher, C. Information resources and productivity. *Information Economics and Policy*, 1983, *1*, 13-35.

Jonscher, C. *Productivity change and the growth of information processing requirements in the economy: Theory and empirical analysis.* Unpublished draft, Cambridge, Mass. , 1982.

Kling, R. Social analyses of computing: Theoretical perspectives in recent empirical research. *Computing Surveys*, 1980, *12*, 61-110.

Kornfeld, W. A. & Hewitt, C. The scientific community metaphor. *IEEE Transactions on Systems, Man, and Cybernetics*, 1981, *SMC-11*, 24-33.

Kraemer, K., & King, J. Computer-based systems for group decision support: Status of use and problems in development. *Proceedings of the Conference on Computer-Supported Cooperative Work*, Austin, Texas, December 3-5, 1986.

Leavitt, H. J. & Whisler, T. L. Management in the 1980's. *Harvard Business Review,* 1958 (November-December), *36 (6)*, pp. 41-48.

Lee, J. & Malone, T. How can groups communicate when they use different languages? *Proceedings of the Conference on Office Information Systems,* Palo Alto, California, 1988.

Lesser, V.R., and Corkill, D.D. The distributed vehicle monitoring testbed: A tool for investigating distributed problem solving networks. *The AI Magazine*, 1983 (Fall), 15-33.

Lowe, D. Co-operative structuring of information: The representation of reasoning and debate. *International Journal of Man-Machine Studies*, 1985, *23*, 97-111.

Mackenzie, K. D. *Organizational Design: The Organizational Audit and Analysis Technology*. Norwood, N.J.: Ablex, 1986.

Malone, T. W. Modeling coordination in organizations and markets, *Management Science*, 1987, *33*, 1317-1332.

Malone, T.W. Organizing information processing systems: Parallels between organizations and computer systems. In W. Zachary, S. Robertson & J. Black (Eds.), *Cognition, computation, and cooperation*. Norwood, N.J.: Ablex Publishing Corp., in press.

Malone, T.W., Grant, K., Lai, K.Y., Rao, R. & Rosenblitt, D.A. Semi-structured messages are surprisingly useful for computer-supported coordination. *ACM Transactions on Office Information Systems*, 1987, *5*, 115-131.

Malone, T. W., Grant, K. R., Turbak, F. A., Brobst, S. A., and Cohen, M. D. Intelligent information sharing systems, *Communications of the ACM*, 1987, *30*, 390-402.

Malone, T.W., & Smith, S. A. Modeling the performance of organizational structures. *Operations Research*, in press.

Malone, T. W., Yates, J., & Benjamin, R. I. Electronic markets and electronic hierarchies. *Communications of the ACM*, 1987, *30*, 484-497.

March, J. G. & Simon, H. A. *Organizations*. New York: Wiley, 1958.

Marschak, J. & Radner, R. *Economic theory of teams*. New Haven, Conn.: Yale University Press, 1972.

McCann, J. and Galbraith, J.R. Interdepartmental relations. In P.C. Nystrom and W.H. Starbuck (Eds.), *Handbook of organizational design*, New York: Oxford Press, 1983, 60-84.

McKelvey, B. *Organizational systemics: Taxonomy, evolution, and classification*. Berkeley, CA: University of California Press, 1982.

Milgrom, P.R. Employment contracts, influence activities and efficient organization design. *Journal of Political Economy*, in press.

Milgrom, P. R. & Geanakoplos, J. A theory of hierarchies based on limited managerial attention. Cowles Foundation Discussion Paper No. 775 and Yale School of Management Sloan Working Paper No. 13, 1985.

Minsky, M. *The society of the mind*. New York: Simon and Schuster, 1987.

Mintzberg, H. *The structuring of organizations*. Englewood Cliffs, N. J.: Prentice-Hall, 1979.

Nii, P. The blackboard model of problem solving. *The AI Magazine*, 1986 (Spring), 38-53.

Nelson, R. & Winter, S. *An evolutionary theory of economic change.* Cambridge, Mass.: Harvard University Press, 1981.

Norman, D. A. Twelve issues for cognitive science, *Cognitive Science,* 1980, *4,* 1-32.

Nyhart & Goeltner. *Computer models as support for complex negotiations.* Working paper, M.I.T. Sloan School of Management, 1955-87.

Pennings, J.M. *Interlocking directorates.* San Francisco: Jossey-Bass, 1980.

Pfeffer, J. Merger as a response to organizational interdependence. *Administrative Science Quarterly,* 1972, *17,* 382-394.

Pfeffer, J. *Power in organizations.* Marshfield, Mass.: Pitman Publishing Co., 1981.

Pfeffer, J. A resource dependence perspective on intercorporate relations. In M.S. Mizruchi and M. Schwartz (Eds.), *Structural analysis of business.* New York: Academic Press, 1986, 117-132.

Piori, M. J. & Sabel, C. *The second industrial divide.* New York: Basic Books, in press.

Reiter, S. Informational incentive and performance in the (new)^2 welfare economics. In S. Reiter (Ed.), *Studies in mathematical economics* (Studies in Mathematics, Volume 25), Mathematical Association of America, 1986.

Robey, D. Computer Information Systems and Organization Structure. *Communications of the ACM,* 1981 (October), 679-687.

Ross, S. The economic theory of agency: The principal's problem. *American Economic Review,* 1973, *63,* 134-139.

Rumelhart, D. E. & McClelland, J. L. (Eds.) *Parallel distributed processing: Explorations in the microstructure of cognition.* Volumes 1 and 2. Cambridge, MA: Bradford Books, 1985.

Sarin, S. & Grief, I. Computer-based real-time conferencing systems. *Computer,* 1985, *18,* 33-45.

Simon, H.A. *Sciences of the Artificial* (2nd Edition). Cambridge, Massachusetts: MIT Press, 1981.

Simon, H.A. *Administrative behavior* (2nd Edition). New York: Macmillan, 1957.

Sluizer, S. & Cashman, P. XCP: An experimental tool for supporting office procedures, *IEEE 1984 Proceedings of the First International Conference on Office Automation,* Silver Srping, MD: IEEE Computer Society, 1984, 73-80.

Smith, R. G. & Davis, R. Frameworks for cooperation in distributed problem solving. *IEEE Transactions on Systems, Man, and Cybernetics,* 1981, *SMC-11,* 61-69.

Stankovic, J., Ramarithm, K. & Cheng, S. Evaluation of a flexible task scheduling algorithm for distributed hard real-time systems. *IEEE Transactions on Computer,* C-34, *12,* December 1985.

Stefik, M. The next knowledge medium. *The AI Magazine,* 1986 (Spring), 34-46.

Stefik, M., Foster, G., Bobrow, D., Kahn, K., Lanning, S. & Suchman, L. Beyond the chalkboard: Using computers to support collaboration and problem solving in meetings. *Communications of the ACM,* 1987, *30,* 32-47.

Taylor, S. The Evolving Legislature: Organizational learning under conflict of interest. *Proceedings of the American Political Science Association Convention*, Washington, D.C., August 31, 1986.

Thompson, J.D. *Organizations in action*. New York: McGraw-Hill, 1967.

Toffler, A. *Future Shock*. New York: Bantam Books, 1970.

Trigg, R. H., Suchman, L. A., & Halasz, F. G. Supporting collaboration in Note Cards. *Proceedings of the Conference on Computer-Supported Cooperative Work*, Austin, Texas, December 3-5, 1986.

Tushman, M. L. & Anderson, P. Technological discontinuities and organizational environments. *Administrative Science Quarterly*, 1986, *31*, 439-465.

Tushman, M. L. & Romanelli, E. Organizational evolution: A metamorphosis model of convergence and reorientation. In L. Cummings & B. Staw (Eds.), *Research in organizational behavior*. Greenwich, CT: JAI Press, 1985.

Virany, B. & Tushman, M.L. Top management teams and corporate success in an emerging industry. *Journal of business venturing*, 1986, *1*, 261-274.

Weick, K. *The social psychology of organizing* (2nd Edition). Reading, MA: Addison-Wesley, 1979.

Whetten, D.A. Interorganizational relations. In J. Lorsch (Ed.), *Handbook of organizational behavior*. Englewood Cliffs, N.J.: Prentice Hall, 1983, 238-254.

Williamson, O. E. The economics of organization: The transaction cost approach. *American Journal of Sociology*, 1981, *87*, 548-575.

Williamson, O. E. The modern corporation: Origins, evolution, attributes. *Journal of Economic Literature*, 1981b, *XIX*, 1537-1568.

Williamson, O. E. *Markets and hierarchies*. New York: Free Press, 1975.

Winograd, T., & Flores, F. *Understanding computers and cognition*. Norwood, N. J.: Ablex, 1986, Ch. 5, 11, 12.

Winter, S.G. The case for 'mechanistic' decision making, in Pennings, H. *et al.*, (Eds.), *Organizational Strategy and Change*. San Francisco: Jossey-Bass, 1985, 99-113.

Winter, S.G. The research program of the behavioral theory of the firm: Orthodox critique and evolutionary perspective. In B. Gilad and S. Kaish (Eds), *Handbook of Behavioral Economics, Vol. A: Behavioral Microeconomics*. Greenwich, CT: JAI Press, 1986, 151-187.