

# What Your Computer Really Needs to Know, You Learned in Kindergarten

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## Abstract

Research in distributed AI has led to computational techniques for providing AI systems with rudimentary social skills. This paper gives a brief survey of distributed AI, describing the work that strives for social skills that a person might acquire in kindergarten, and highlighting important unresolved problems facing the field.

## Introduction

In the pursuit of artificial intelligence (AI), it has become increasingly clear that intelligence, whatever it is, has a strong social component [Bobrow, 1991; Gasser, 1991]. Tests for intelligence, such as the Turing test, generally rely on having an (assumedly) intelligent agent evaluate the agent in question by interacting with it. For an agent to be intelligent under such criteria, therefore, it has to be able to participate in a society of agents.

Distributed AI (DAI) is the subfield of AI that has, for over a decade now, been investigating the knowledge and reasoning techniques that computational agents might need in order to participate in societies. Distributed AI researchers have come from a particularly diverse set of backgrounds, ranging from distributed computing systems to discourse analysis, from formalisms for representing nested beliefs in agents to cognitive studies of human performance in organizations, from solving inherently distributed problems in applications such as communication network management to analyzing the evolution of cooperation in populations of artificial systems. The wealth of the field of DAI lies in its interdisciplinary nature, generating a melting pot of ideas from people with widely different perspectives who share a common goal of realizing in computers many of the social capabilities that we take for granted in people.

In studying these capabilities, it is helpful to consider how people become socialized. In our modern

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culture, one important socialization step happens when a child enters school. In his book *All I Really Need to Know I Learned in Kindergarten*, Robert Fulghum lists sixteen things he learned in kindergarten that, he claims, form a core of knowledge and skills that he has used throughout life [Fulghum, 1986]. Now, while this list is anecdotal, I would argue that it is not by chance that the majority of the items he lists, ten of the sixteen, deal with social knowledge and skills.

In fact, these ten items in Fulghum's list have strong correspondence to exactly the issues that DAI researchers confront. In this paper, therefore, I will use Fulghum's points to structure my brief survey of the field. My goals are twofold. First, while I cannot give in this small space as thorough a treatment of the field as can be found elsewhere [Bond and Gasser, 1988; Durfee *et al.*, 1989; Durfee *et al.*, 1991; Gasser and Huhns, 1989; Huhns, 1987], I do want to provide pointers to more detailed descriptions of individual research projects. Second, I want to use Fulghum's points as a way of clustering work together with perhaps a little bit different a spin. This helps highlight open and unresolved issues within DAI, and hopefully might give the DAI melting pot another little stir.

## Share Everything

When resources like information, knowledge, and authority are distributed among agents, agents might need to share to accomplish their tasks. Task sharing and result sharing have been investigated in DAI [Smith and Davis, 1981]. In task sharing, an agent with a task that it cannot achieve will try to pass the task, either whole or in pieces, to agent(s) that can perform the task(s). Generally, task passing is done through some variation of contracting. As developed in the Contract Net protocol [Smith, 1980], the agent that needs help assigns tasks to other agents by first announcing a task to the network, then collecting bids from potential contractors, and then awarding the task to the most suitable bidder(s). Note that both the initial agent (manager) and the eventual contractor(s) have a say in the assignment: a contractor chooses whether to bid or not (and how much), and a manager

chooses from among bidders. Tasks are thus shared through *mutual selection*.

Whereas task sharing is generally used to break apart and distribute pieces of large tasks, result sharing takes the opposite view. Specifically, some problems are inherently distributed, such as monitoring the global stock market, or national aircraft traffic. The challenge with these problems is getting agents, who have small local views, to share enough information to formulate a complete solution. This style of distributed problem solving has been termed functionally accurate, cooperative [Lesser and Erman, 1980; Lesser and Corkill, 1981; Lesser, 1991]. At any given time, an agent might use its local view to generate partial solutions that are, in fact, incompatible with the solutions of other agents. However, given enough sharing of information, and strong assumptions about agent homogeneity (that if agents have the same information they will derive the same solutions), complete solutions will emerge eventually.

Of course, the wholesale exchange of every partial solution among all agents is far from an appealing prospect. Substantial work, much of which we will see in later sections, has gone into ways of being more selective of what is sent and when. For example, in DARES [Conry *et al.*, 1990; MacIntosh *et al.*, 1991] a network of theorem proving agents, each of which begins with a subset of the complete set of axioms, will request partial solutions (axioms) from each other when they are stuck or otherwise making poor progress. A request can specify characteristics of axioms that could be useful, to avoid exchanging useless information.

Sharing is clearly a useful approach, but it makes some very strong assumptions that are certainly not universally embraced. In particular, it generally assumes a common language for tasks and/or results that has identical semantics at each agent. Researchers concerned with modeling people recognize that people cannot be assumed to ever attribute precisely identical semantics to a language. However, the counterargument is that computers *can* be programmed to have precisely identical semantics (so long as they cannot modify themselves). Moreover, as evidenced in human coordination, identical semantics is not critical, so long as satisfactory coordination can arise.

### Play Fair

In both task sharing and result sharing, agents are assumed to want to help each other. The contracting approach generally assumes that any agent that can do a task and is not otherwise committed will be happy to take on a task. Similarly, in result sharing, agents voluntarily pass around information without any expectations in return. Benevolence on the parts of these agents stems from an underlying assumption of many coordination approaches: That the goal is for the system to solve the problem as best it can, so the agents have a shared, often implicit, global goal that they all

are unselfishly committed to achieving. Load is to be balanced so that each agent will perform its fair share of the task.

Some researchers argue that shared goals, and the resultant *benevolence assumption* [Rosenschein *et al.*, 1986], are artificial and contrived. Autonomous agents cannot be instilled with common goals, but instead must arrive at cooperation based on being selfish. However, other researchers argue that, first of all, the agents we are building are artificial, and so can be built with common goals if desired. Moreover, common goals even among adversaries seem to be prevalent: opposing teams on the field have a shared goal of having a fair competition.

Thus, even having the agents share a common, high-level goal will not guarantee compatibility among their actions and results. For example, even though specialists in the fields of marketing, design, and manufacture might share the goal of making a quality, profitable car, they still might disagree on how best to achieve that goal because each interprets that goal using different knowledge and preferences. Participating in a team like this requires negotiation and compromise. While contracting demonstrates rudiments of negotiation due to mutual selection [Smith and Davis, 1983], a broad array of more sophisticated techniques have emerged in this area, including using cases and utility theory to negotiate compromises [Sycara, 1988; Sycara, 1989], characterizing methods for resolving different impasse types [Klein, 1991; Lander *et al.*, 1991; Sathi and Fox, 1989], proposing alternative task decompositions given resource constraints [Durfee and Lesser, 1991], and using the costs of delay to drive negotiation [Kraus and Wilkenfeld, 1991].

### Don't Hit People

As discussed above, distributed problem solving generally assumes that, at some level, agents implicitly or explicitly have some commonality among their goals. This assumption is really a result of the perspective taken: that the focus of the exercise is the distributed problem to be solved. Rather than look at DAI systems from the perspective of the global problem, many researchers have looked at it instead from the perspective of an individual. Given its goals, how should an individual take actions, coordinate, and communicate if it happens to be in a multiagent world?

Following the same spirit as in the influential work of Axelrod on the evolution of cooperation among self-interested agents [Axelrod, 1984], a number of DAI researchers have taken the stance of seeing an agent as a purely selfish, utility-maximizing entity. Given a population of these agents, what prevents agents from constantly fighting among themselves?

Surprisingly, cooperation can still emerge under the right circumstances even among selfish agents, as Axelrod's initial experiments showed. The rationale for this result can be found in different forms in the DAI

literature. One approach is to consider what agents can know about other agents. Rosenschein and his colleagues have considered different levels of rationality that agents can use to view each other [Rosenschein *et al.*, 1986]. With strong rationality assumptions, an agent that might separately consider a nasty action could reason that, since I assume that the other agents are just like me, we will all take the same action. With that deduction, the agents might jointly take cooperative actions, as shown in the prisoner's dilemma. Moreover, given the ability to communicate, rational agents can strike deals even in adversarial situations [Zlotkin and Rosenschein, 1991].

Another strong motivation for agents being "nice" is that agents might encounter each other repeatedly, and so they might be punished for past transgressions. An agent might thus determine that its long-term payoff will be better if it does not antagonize another. This intuition has been captured [Gmytrasiewicz *et al.*, 1991a; Vane and Lehner, 1990], and has introduced the game theoretic definition of cooperation—as what agents will do if they expect to interact infinitely many times—into DAI.

### Put Things Back Where You Found Them

Agents that share a world must contend with the dynamics that each introduces to the others. Given realistic assumptions about uncertainty in communication and observation, it will generally be the case that the agents can never be assured to have completely "common knowledge" about aspects of the world they share, including what each other knows and believes [Halpern and Moses, 1984].

Several strategies to deal with this dilemma have been studied. One strategy is to have each agent take situated actions, essentially treating other agents as generators of noise who change the world in (possibly) unpredictable ways and with whom coordination is either impossible or not worthwhile. We'll get back to this strategy in a later section. Another strategy is to have agents try to make minimal changes to the world so as to not violate the expectations of others. For example, the work by Ephrati and Rosenschein [Ephrati and Rosenschein, 1992] examines how an agent that is acting in the world can choose its actions so as to achieve a state of the world that it believes another agent expects. This is a more sophisticated variation of putting things back where you found them so that others can find them later.

Rather than trying to maintain the world in a somewhat predictable state, the agents can instead communicate about changes to the world, or of their beliefs about the world. In this strategy, agents that need to maintain consistent beliefs about some aspects of the world use communication to propagate beliefs as they change nonmonotonically, performing distributed truth maintenance [Bridgeland and Huhns,

1990; Doyle and Wellman, 1990; Huhns and Bridgeland, 1991; Mason and Johnson, 1989]. More generally, agents can use communication to ensure that their expectations, plans, goals, etc. satisfy constraints [Conry *et al.*, 1991; Yokoo *et al.*, 1990]. Of course, making such communication decisions requires planning the impact of each communication action [Cohen and Perrault, 1979] and modeling joint commitments to activities [Levesque *et al.*, 1990].

Finally, some research has assumed that agents should communicate to improve consistency in how they expect to interact, but should permit some inconsistency. In essence, the agents should balance how predictable they are to each other (to improve consistency) with the need to respond to changing circumstances [Durfee and Lesser, 1988]. At some point, it is better to settle for some degree of inconsistency than to expend the resources on reaching complete agreement. This idea has been a fundamental part of the partial global planning approach to coordination, its extensions, and its relatives [Carver *et al.*, 1991; Decker *et al.*, 1990; Durfee, 1988; Durfee and Lesser, 1991; Durfee and Montgomery, 1991].

### Clean Up Your Own Mess

Like putting things back, cleaning up your own mess emphasizes taking responsibility for an area of the shared, multiagent space. Some DAI researchers have approached the problem of coordination from the perspective of organization theory and management science, which sees each agent as playing one or more roles in the collective endeavor. Organizations arise when the complexity of a task exceeds the bounds of what a single agent can do [Fox, 1981; Malone, 1987; March and Simon, 1958]. Within an organization, it is important that each agent know what its own role is and what the roles of other relevant agents are.

Organizational structuring has been employed as a technique for reducing the combinatorics of the functionally accurate, cooperative paradigm [Corkill and Lesser, 1983]. The essence of this approach is that each agent has common knowledge of the organization, including its own interests and the interests of others. When it has or generates information that could be of interest to another agent, it can send that information off. While playing its role in the organization, an agent is free to take any actions that are consistent with its role. Thus, organizations provide a flexible coordination mechanism when roles are defined broadly enough, although incoherence can arise if the roles are defined too broadly [Durfee *et al.*, 1987].

### Don't Take Things That Aren't Yours

Conflict avoidance has been a fundamental objective of DAI systems. Because goal interaction has also been at the forefront of AI planning research, it is not surprising that the initial meeting ground between planning

and DAI was in the area of synchronizing the plans being carried out at different agents to ensure proper sequencing of actions to avoid having the actions of one agent clobber the goals already achieved by another. Among the efforts in this area have been techniques by which a single agent can collect and synchronize the plans of multiple agents [Cammarrata *et al.*, 1983; Georgeff, 1983] and by which multiple agents can generate their plans and insert synchronization in a distributed fashion [Corkill, 1979].

Similarly, resource contention has been critical in scheduling applications. Identifying and resolving constraint violations in allocating and scheduling resources has continued to be of interest in DAI [Adler *et al.*, 1989; Conry *et al.*, 1991; Sycara *et al.*, 1991].

While important, there is more to cooperation than only avoiding conflicts. Even when there is no conflict, coordination could still be beneficial, leading agents to take actions that mutually benefit each other even though they could have acted alone. But deciding how to search for such beneficial interactions, and how much effort to exert in this search, is a difficult problem [Durfee and Montgomery, 1991; von Martial, 1990].

### Say You're Sorry When You Hurt Someone

If we had to decide from scratch how to interact whenever we encountered another person, we would never get anything done. Fortunately, most encounters are of a routine sort, and so we can fall back on fairly complete plans and expectations for interaction. I use the term "protocol" to represent the expectations that agents use to structure an interaction. We have seen already some examples of protocols, most notably the contract net in which agents use specific message types for communication, along with expectations about the impact of a message (that a task announcement will elicit a bid, for example).

Most DAI research has rested on providing agents with explicit, predesigned, unambiguous communication protocols. Agents will often exchange expressions in first-order logic, or exchange frames representing plans or goals, or exchange some other structured messages with assurance that others will know how to treat them. Given that we can construct agents as we desire, assuming not only a common language but also a common protocol to structure how the language will be used is not unreasonable.

However, a number of researchers both within DAI and without have been investigating more deeply questions of how communication decisions might be made when explicit protocols are not assumed, based on the intentions and capabilities of the agents involved [Cohen and Levesque, 1990; Grosz and Sidner, 1990; Werner, 1989; Singh, 1991]. As an example of such an approach, a selfish utility-maximizing agent will not necessarily want to communicate based on some pre-

defined protocol (although it might have advantages), but instead might want to consider what messages it could possibly send and, using models of how the impacts of the messages on others might affect interactions, choose to send a message that is expected to increase its utility [Gmytrasiewicz *et al.*, 1991b]. In fact, agents might intentionally choose to lie to each other [Zlotkin and Rosenschein, 1990]. One exciting opportunity for further research is investigating how protocols and truth-telling can arise through repeated communication among individuals, much as cooperation can arise among the actions of selfish agents engaged in repeated encounters.

### Flush

Just as apologizing for hurting someone is an expected protocol when it comes to communication actions, so also is flushing an expected protocol for interacting through a reusable (but not shared!) resource in the environment. We might term such protocols for non-communicative interaction *conventions*. For example, we follow conventions to drive on a particular side of the road, to hold the door for others, to clasp a hand extended for a handshake, and so on.

Because conventions seem to be, in some sense, something shared among agents in a population, they have much in common with organizational structures which similarly guide how agents should act when interacting with others. Unlike organizational structures, however, in which different agents have different roles, conventions carry the connotation of being laws that everyone must obey. Recent work has been directed toward the automatic generation of such social laws [Shoham and Tennenholtz, 1992]. With such laws, agents can reduce the need for explicit coordination, and instead can adopt the strategy (mentioned previously) of taking situated actions, with the restriction that the actions be legal.

Important, and so far little explored, questions arise when agents must act in concert with little or no pre-arranged organization or laws, however. For example, what happens if people that had expected to stick together suddenly find themselves separated? What should they decide to do in order to find each other? Most likely, they will try to distinguish particular unique locations for finding each other (the car, the lobby, ...) that each believes the other will distinguish too. The same ideas are being considered now in DAI, with questions arising as to how such distinguished places, or *focal points*, can be found by an artificial agent [Kraus and Rosenschein, 1991].

### When You Go Out into the World, Watch for Traffic, Hold Hands, and Stick Together

Unlike the previous bits of coordination knowledge, which had to do with how to behave in your own

group, this suggestion shows us a bigger world, comprised both of friends (with whom you stick) and enemies (traffic). This highlights a fundamental aspect of cooperative activity: That cooperation often emerges as a way for members of a team to compete effectively against non-members. In turn, this means that organizations don't simply begin full grown, but instead they emerge as individuals form dependencies among each other as a means to compete against outside individuals more effectively.

The idea of organizations emerging and evolving, while acknowledged in early DAI work, has only recently been given due attention. Based on sociological ideas, Gasser's work has emphasized the dynamics of organizations [Gasser *et al.*, 1989], and in joint work with Ishida has explored techniques for organizational self-design [Gasser and Ishida, 1991]. Research on computational ecologies [Hogg and Huberman, 1991; Kephart *et al.*, 1989] has similarly been concerned with how agent populations will evolve to meet the needs of a changing environment.

### Eventually, Everything Dies

This is my paraphrase for one of Fulghum's points. From a DAI perspective, I see its meaning as reminding us of one of the primary motivations for DAI, or for group activity in general. That is, you cannot count on any one individual to succeed. The chances of success are improved by distributing responsibility, and reliance, across a number of agents so that success can arise even if only a subset of them succeed.

The fact that populations of agents change emphasizes the open nature of DAI systems, where a (relatively) static organizational structure will be ineffective due to the dynamically changing composition of the agent population. The open system's view maintains that agents take responsibility for themselves, and that they form commitments dynamically [Hewitt and Inman, 1991; Gasser, 1991]. Much of this work is based on the influential ACTORS formalism [Hewitt, 1977; Kornfeld and Hewitt, 1981; Ferber and Carle, 1991].

### Conclusion

A goal of AI is to endow computer systems with capabilities approaching those of people. If AI is to succeed in this goal, it is critical for AI researchers to attend to the social capabilities that, in a very real sense, are what give people their identities. In this paper, I have used a list of important knowledge and skills learned in kindergarten as a vehicle for illustrating some of the social capabilities that computers will need. I have described some of the work in DAI that has explored computational theories and techniques for endowing computers with these capabilities, and I have also tried to convey the diversity of perspectives and opinions even among those doing DAI about appropriate assumptions and about what problems are the important ones to solve. As I see it, all of the problems

are important, and we have a long and exciting road ahead of us to build a computer system with the same social graces as a kindergarten graduate.

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