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Abstract

The natural and social sciences have recognized for some time that when rational agents use a shared resource (a "commons") near its capacity, the resource is doomed. This is the *tragedy of the commons*. The same problem will also arise when agents in a distributed AI system share a resource. In this paper, we examine the tragedy of the commons as it applies to DAI and discuss several potential solutions, including conventions, privatization of the resource, and mutual coercion mutually agreed upon. Solutions to this problem in DAI testbeds will likely also contribute to understanding how to avoid the tragedy of the commons in many areas of current interest to society, such as fisheries management, preservation of whale and other species populations, global climate change, and preservation of tropical rainforests.

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In 1968, biologist Garrett Hardin brought to science's attention a little-known work by the nineteenth century amateur mathematician William Forster Lloyd on population growth and control [Hardin, 1968]. Lloyd examined the fate of a common pasture shared among rational, utility-maximizing herdsmen. With increasing population, the pasture is inevitably destroyed. Hardin showed that Lloyd's work has widespread implications not only for population control, but also for the overexploitation and eventual ruin of any resource held in common (a "commons"). This includes both resources that are harvested, such as whales, as well as resources that are used as depositories of waste, such as the air and oceans. Every resource has a *carrying capacity* [e.g., Ricklefs, 1990], the maximum amount of use it can support. Once a resource is being utilized at a rate near its carrying capacity, additional utilization will degrade its value to its current users. Users then will enter into a cycle of additional use of the resource to gain or to try to break even as others use it. Since all users engage in this behavior, the resource is ultimately and inevitably doomed: "Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons" [Hardin, 1968]. The inexorable working out of the resource's ruin is Hardin's *tragedy of the commons*.

In human affairs, the tragedy of the commons has never been more evident than it is today, as we face its effects of pollution, global warming, ozone depletion, overfishing and extinction of species, and destruction of the rain forests. But what relevance does it have for distributed artificial intelligence (DAI)?

We argue that a DAI system composed of rational agents will encounter the tragedy of the commons just as a collection of humans will. This applies whether the agents are cooperative, antagonistic, or neutral. Many examples of shared resources that are at risk exist, including processing capacity on a shared processor, memory, disk space, power, physical space and materials, and communication channel bandwidth. As with any other commons, the agents will tend to overutilize the resource to the detriment of all. DAI researchers need to understand the problem in order to avoid the destruction of resources necessary for their systems' missions. DAI systems can also play a valuable role in averting the tragedy of the commons in many areas of current interest to society by serving as testbeds for developing and evaluating new policies.

Since the barrier between the natural and computer sciences is often high and opaque, we first discuss the tragedy of the commons in more detail, then how it impacts DAI systems. Finally, we discuss some solutions that have been proposed for human systems and their applicability to DAI.

The Tragedy of the Commons

Lloyd's original formulation of the problem was in terms of a common pasture shared by many herdsmen, a common early practice in this country and also in England until the middle of the last century. The system of the commons will work as long as the number of cattle (N) is less than the number the pasture can support (carrying capacity, K). When $N < K$, each head of added cattle is pure gain for the herdsman, without disadvantaging others. When N approaches K, however, this is no longer true; when $N \geq K$, adding another head decreases the quality of grazing for all. We can see that the question facing the herdsman is [Hardin, 1968]: "What is the utility *to me* of adding one more animal to my herd?"

The problem arises because the costs of using the resource are distributed differently than the gains. The gain accrues only to the herdsman and is nearly one;[1] the loss is due to overuse and damage to the commons and therefore to the value of each head grazing. This loss, however, is spread among *all* herdsmen (the "spillover cost" [Baden, 1977]), so the loss to the offending individual is slight. Thus the utility of adding a head of cattle is positive, and a rational, maximizing herdsman will do so. Since all herdsmen are rational, they will each add a head, and another, and... Ultimately, the resource is exhausted. This intuitive argument has been corroborated both by game theory [Muhsam, 1973] and modeling by differential equations [Anderson, 1974].

The problem is more insidious than we might first imagine. Overuse of many kinds of resources, such as a pasture, leads to irreparable damage [Hardin, 1977]: trampling by cattle packs the ground, and overgrazing facilitates the conversion from grassland to a weed field.[2] In addition, it is not just greed that leads to resource destruction. Using game theory, Muhsam [1973] has shown that if some or all other herdsmen add cattle when $N \geq K$, an individual *must* add a head if he or she wishes to reduce the loss suffered as a result. A rational agent will have no choice but to add to the herd, and hence, to the problem. The "tragedy" is in the sense of dramatic tragedy, what Whitehead has termed the "remorseless working out of things" [Hardin, 1968].

The tragedy of the commons has dire implications for any commonly-held resource being utilized near K,[3] not just pastures. For example, the collapse (or near collapse) of once-great fisheries and whale populations is a direct consequence of over-exploitation brought about by the world's maritime nations treating the ocean as a commons [Hardin, 1977], and the rainforests in South America are threatened because they, too, are treated as a commons.

Consumable resources are not the only ones endangered by a system of commons, as Hardin [1968; 1977] is quick to point out. Pollution of a resource is the flip side of the problem when the cost to the polluter of degrading the resource (e.g., by dumping wastes into the air or water) is less than the cost to him or her of not degrading it (e.g., treating wastes before release). Thus we see the tragedy being played out in the ozone layer, pollution, and global climate changes.

The Tragedy of the Commons and DAI

The tragedy of the commons only requires that agents holding a resource in common be rational, not that they be human. Consequently, a DAI system will also fall prey to

[1] In terms of heads of cattle, fed when the resource is not stressed; it would be exactly one if N were less than K.

[2] This assumes constant disturbance (e.g., by continued grazing), since weeds, being relatively r-selected [Ricklefs, 1990], will likely not be the climax community; the climax community, however, would probably not be pastureland again, either.

[3] Which, via the motive of profit or the pressure of increased population, will ultimately be the fate of almost any resource.

the problem when it relies on a common resource shared among its agents. The system's resource will also be at risk when external agents (human or otherwise) utilize it. In the pristine world of the laboratory, this concern may be merely academic; however, once DAI systems are fielded for long periods in the real world, tackling real, complex problems, the potential for the tragedy of the commons leading to the destruction of critical resources becomes all too real.

There are many resources a DAI system's agents may hold in common. The most obvious cases of such "common pool resources" [Baden, 1977] are when DAI agents act as avatars for humans, for example to harvest a natural resource (such as fish or trees) that is already being exploited at or near its carrying capacity. Here the task *is* the utilization of the commons. Unless the agents have the authority and ability to set their own policies with regard to using the resource, they will contribute to the ruin of the resource in the same way and for the same reasons as do humans.

The more interesting case is when the agents' use of common resources is not their primary task, but rather is instrumental to their assigned tasks, since here the agents' own policies affect the fate of their resources. Examples of resources that DAI agents might share include: physical resources (e.g., raw materials) that are used to construct something; power obtained from a slowly-recharging refueling point; information from an external sensor; message traffic on a shared communication channel (such as an Ethernet or an acoustic communication link [e.g., McCue *et al.*, 1991; Turner *et al.*, 1991]); or cycles, memory, or disk space on a shared processor. Situations may also arise in which agents utilize a common area or resource for disposing of waste heat or material. Figure 1 summarizes the properties of a few common resources for DAI systems.

	Traditional	**Processor**	**Communication Channel**	**Power**	**Sensor**	**Sonar**
Resource	grass	cycles	bandwidth on shared channel	power from renewable resource	access to sensor	quiet environment
Consumers	cattle	processes	conversations (messages)	agents	agents	agents' sonar
Action	grazing	computation	sending messages	recharging	access	sonar pulses
Owners	herdsmen	DAI agents	DAI agents	DAI agents	DAI agents	DAI agents
Gain	head of cattle	increased throughput	inc. message throughput	inc. ability to work	accuracy, decreased uncertainty	accuracy, decreased uncertainty
Cost	decreased quality per head, degraded pasture	dec. speed/process	noise, collisions, dec. speed of delivery	dec. power to others	dec. access for others, overhead for sensor	noise$\Rightarrow$sonar interference
Result	collapse of pasture (poss. irrecoverable)	thrashing, unacceptable throughput	contention	contention for power, some may be out of power	"starvation" for sensor data, sensor processing or message overload	inability to use sonar

Figure 1: Examples of resources which may be shared by DAI agents. (Column two is provided for reference to the classic statement of the tragedy of the commons.)

An example. Suppose several autonomous underwater vehicles (AUVs) are carrying out tasks in a particular area. Each AUV needs to locate objects in its environment, including the other AUVs, via its sonar; assume that the sonars all operate at about the same frequency. Sonar sends acoustic energy into the water column, which is the "commons" in this case; the commons is "depleted" by the addition of acoustic noise that interferes with sonar. An AUV benefits by increasing its sonar use, since it thereby gains an increasingly accurate picture of its world. However, in so doing, it degrades to some extent its and other agents' sonar data quality. The benefit of increased information accruing to the AUV will outweigh the shared disadvantage of an increased noise level shared by all AUVs, thus leading rational AUV controllers to increase their sonar output, either in terms of number of sonar pulses or by amount of energy per pulse (to punch through the noise). This can ultimately lead to the "collapse" of the commons when the noise is great enough to render all AUVs' sonars useless.

Agent characteristics. Characteristics of the agents and the DAI system as a whole affect the tendency toward the tragedy of the commons. One predisposing factor is if agents have some goals that are solely their own, either entirely unrelated to group goals or else subgoals pursued independently (e.g., as in the contract net protocol [Smith, 1980]). The DAI community knows that Adam Smith's "invisible hand" doesn't necessarily hold for our systems—agents acting in their own self-interest are not necessarily led to work toward the common good—else DAI researchers would not need to expend so much effort on issues of coherence and coordination [e.g., Fox, 1981; Durfee *et al.*, 1987]. The tragedy of the commons, which is brought about by agents pursuing their own goals, is another "rebuttal to the invisible hand" [Hardin, 1968]. Agents with their own goals to achieve will select those actions that further those goals. To avoid this requires short-term sacrifices (in terms of goal achievement) in return for long-term gains (health of the resource). It also requires that the agents have enough global knowledge to realize that there *are* long-term dangers and gains due to the common resource. Unless the designers of the system take pains to ensure that there are shared goals of preserving the commons and that these have priority over individual goals, the commons is in danger.

A second important characteristic is whether or not the agents are cooperative, or at least benevolent. Antagonistic or neutral agents have no real motivation to preserve a commons for "the greater good". At least with cooperative agents, there is a *chance* for some appeal to the common good to motivate moderation on the part of an agent's use of the resource.

The ability to coordinate the actions of the agents via some sort of organization or coordination strategies also impacts the system's predisposition to the tragedy of the commons. In the absence of strict limits that each agent independently observes,[4] coordination is necessary to determine, monitor adherence to, and maintain resource utilization policies [Ostrom & Ostrom, 1977; Baden, 1977]. How tightly the agents are coupled to one another is also important. With loosely-coupled agents, there is less chance for coordination of the commons' use, even when it has been identified and policies are in place to preserve it. In some systems, such as those using the contract net protocol, agents may not even know about the existence of their peers; in such situations, it will be very difficult to manage the commons.

Communication is an important factor in avoiding the problem, since without it, agents may not be able to coordinate their actions to avoid destroying the resource. The tragedy of the commons has been likened to the "prisoner's dilemma" [Muhsam, 1973]; Rosenschein and Genesereth [1985] have shown that communication, at least of a particular kind (deals), under some conditions can provide a way to solve this dilemma to the mutual satisfaction of the participants.

One property of agents that must be guarded against if the tragedy is not to be played out

[4] Which ultimately arise from some sort of coordination and may not, in any case, preserve the commons: witness the problem of attaining the "maximum sustainable yield" in fisheries by setting catch limits.

to the bitter end is an outright willingness on the part of the agents to destroy the commons, what has been called "killing the goose" [Fife, 1971]. This happens when agents (or their missions, in the case of DAI systems) can survive the destruction of the common resource. For example, a corporation may hunt a species to extinction, then switch to another species; or it may invest its profit from destroying a resource at a rate that allows it to survive (and perhaps prosper) after the resource is destroyed. A DAI system might do something similar, at least on a local level. For example, a group of AUVs may be told to gather all the sea urchins they can in a given period of time. If they are unleashed in an area of the Gulf of Maine that is already being fished for urchins, there is a good chance that they will cause the local extinction of the species in that area. They can then move on to another mission, but for the urchin fishermen in that area, the resource has been destroyed.

Figure 2 shows where some common approaches and systems fall with respect to three important axes, ability for global coordination, communication, and autonomy. In general, the closer to the origin a system lies, the better off it is with respect to the problem of the commons. Some approaches, such as multiagent planning [e.g., Cammarata *et al.*, 1983; Georgeff, 1984], would seem to be fairly safe; however, as we discuss below, there are important caveats.

Figure 2: Relation of several DAI approaches/systems with respect to three important characteristics. CNET=contract net protocol; MAP=multi-agent planning; FA/C=functionally-accurate, cooperative [Lesser, 1991]; AUV=a system of autonomous agents, such as AUVs [Turner et al., 1991].

Domain and resource characteristics. Characteristics of the domain and resource also affect the problem. It has generally been assumed in the literature on the tragedy of the commons that agents can first perceive that there *is* a commons and then can determine the state of that commons. This is a questionable assumption even for human systems, but it is even worse for DAI systems operating in real-world domains. Such domains generally involve high levels of uncertainty and/or incomplete knowledge, brought about not only by inherent ignorance of some properties of the domain, but also by complexity and by sensor limitations of the agents. Agents will likely not know the status of their shared resource or the actions of their peers with any great degree of certainty—in the worst case, they may not even recognize the presence of a commons or other agents. Under these conditions, the destruction of the commons will be greatly accelerated, and policies to prevent it will be thwarted.

A second property of the domain that is important is the utilization of the resource. We have assumed until now that $N \geq K$. In many situations, however, this will not be the case for DAI systems, as there may be more power, processor cycles, disk space, or channel bandwidth available than needed. Even here, however, we still need to worry about the tragedy of the commons. The first problem is the slippery definition of the word "needed". If enough resources are available to completely satisfy all agents' goals related to that resource, then there will be no problem. However, if the goals are of the type that admit to varying degrees of satisfaction proportional to the amount of resources used (such as "obtain wealth" for humans and human corporations, or "increase number of tasks completed" for DAI agents), then the commons is doomed without effective management. The second problem is that realistic and useful DAI systems will seldom if ever operate in isolation, that is, when there are not also other agents present that are not part of the DAI system. If a resource is not totally under the control of the system, then even if there is enough of the resource to meet the needs of the system, we still cannot guarantee that the tragedy will be averted. In such cases, agents external to the system may use the resource, ultimately forcing the system to overuse it in a vain attempt to break even.

Figure 3 summarizes the impact of agent and domain characteristics on the problem.

Agent characteristics:

- Goals that are independently worked on (+)
- Cooperative (−)
- Coordination (−)
- Communication (−)
- Willingness to "kill the goose" (+)

Domain/resource characteristics:

- Uncertainty/incomplete knowledge (+)
- Utilization of resource
    - near K (+)
    - below K (+?)

Figure 3: Summary of characteristics predisposing to (+) or protecting against (−) the tragedy of the commons.

Toward Solutions

The first step in averting the tragedy of the commons is to recognize that there *is* a commons, a kind of situation assessment. This step is often overlooked by humans in managing common pool resources until N approaches or exceeds K. From the standpoint of DAI, when the agents involved are part of a cooperative distributed problem solving (CDPS) system, we would seem to be in a good position to avoid this problem. By careful examination of the task and the agents' characteristics, it may be possible to determine ahead of time what resources the agents need to share and institute some mechanism for their control. However, even with CDPS systems, it may not be that simple. Ultimately, we would like DAI systems to be deployed for long periods of time in the real world. Consequently, over their lifetime they will face changing conditions and intra- and inter-system interactions that bring about new common pool resources. Also, CDPS is only one facet of DAI—agents may be antagonistic, neutral, or not under any single designer's control—and seldom, as we have pointed out, will a system operate completely apart from other agents that may share its resources. Given this, agents need diagnostic abilities and the requisite information to identify common pool resources before their management becomes a problem.

Existing DAI solutions. Some existing approaches in DAI can potentially mitigate the problem of managing common pool resources. Multiagent planning approaches [e.g., Cammarata *et al.*, 1983; Georgeff, 1984] would seem to be one solution to the tragedy of the commons. In these systems, one agent is designated as planner; it then makes resource allocation decisions for all the others and serves as arbiter should problems arise. Unfortunately, multiagent planning approaches have severe problems in complex, uncertain domains, which are just the domains where the tragedy of the commons is most likely to occur. The planning agent needs nearly perfect knowledge of the other agents, the environment, and especially the shared resources to create reasonable plans. Demands on the agent's rationality may be extremely high in complex tasks or environments. In addition, the agent selected as the planner may not be the best one, either in terms of having access to the knowledge and/or authority it needs to make and enforce its decisions or because it has some personal interest in the resource that influences its decisions.

Partial-global planning [Durfee & Lesser, 1987] and other work on functionally-accurate, cooperative (FA/C) systems [e.g., Lesser, 1991], could also address the problem. In this approach, agents share information (such as goals and plans) and ultimately can form joint plans spanning much of problem space and encompassing many or even all of the agents. Resource contention in a system like this can be ironed out via negotiation, at least in theory, though it is more difficult to see how long-term common pool resource management issues might be introduced and resolved.

Other approaches exist as well that might be able to address the problem [e.g., Kornfeld & Hewitt, 1981], though for some (such as the contract net protocol) it would be difficult. In general, very little work has been done in DAI specifically on the common pool resource management problem. For potential solutions, we must turn to work on common pool resource management in human systems.

Voluntary measures and conventions. It would at first seem that voluntary measures, such as conventions or bargaining, would be adequate for averting resource destruction. However, for resources used by humans, voluntary measures such as appeals to conscience will not work [Hardin, 1968; Hardin, 1977]. One problem with voluntary ("private") solutions is the free-rider problem [Baden, 1977]. For example, why should you pay for a road when you know all your neighbors will, and you will be able to use it regardless? In the long-term, it can be shown that conscience with respect to using crucial resources is self-eliminating [Hardin, 1968; Hardin, 1977]. A problem with bargaining as a voluntary means of controlling resource use is the cost of the decision making or bargaining process [Baden, 1977]. But will voluntary approaches work for DAI systems, where designers have more control over what agents will or will not do?

Conventions or heuristics for resource use will only work when the designers have complete control over all the agents. If the DAI system interacts with other agents via a shared resource, the only effect of the conventions will be to put it at a competitive disadvantage relative to the other agents. The mechanism will also fail when one or more of the agents have goals that have higher priority than following the conventions. This could happen either due to an agent's private goals (e.g., "survival", or goals unrelated to its participation in the DAI system) or goals arising as subgoals of the goals of the DAI system as a whole. Bargaining approaches suffer from decision-making or bargaining costs, and, since DAI systems in the real world will operate under conditions of limited rationality and communication channel bandwidth, these costs may be too high for realistic implementation. Uncertainty will undermine the efficacy of both shared conventions or bargaining, leading agents to use more of the resource than they should due to faulty sensing of the state or their use of the resource, or the conventions or bargains struck may themselves allow overuse due to uncertainty.

Monopolies. Use of a common pool resource by multiple agents can engender competition for the resource [Ostrom & Ostrom, 1977]. One endpoint of competition is a monopoly, in which one agent effectively "owns" the resource and excludes all others (similar to the concept of *competitive exclusion* in ecosystems). Allowing a monopoly has little appeal in most human affairs, but what about for DAI systems? In some respects, a monopoly in which an agent owns a resource and determines how it is used is much like multiagent planning, with many of the same drawbacks—especially given the likelihood that the agent will have a personal stake in the management of the resource. The process of competition leading to the monopoly's formation may also be inefficient with respect to the agents' goals and may itself ruin the commons.

Privatization. One widespread solution to managing common pool resources is to turn them into privately-owned resources by splitting them and assigning ownership. As Hardin [1977] points out, this is indeed one way to avoid the tragedy of the commons, since any costs due to destruction of a portion of the resource then falls completely on the head of its owner/user, with no spillover costs to others. The major dangers of privatization are: (1) if the privateer can destroy his or her resource while investing the proceeds, he or she may choose to do so [Hardin, 1977]; and (2) ensuring that all potential users of the resource receive their fair share of it.

Privatization may work for some resources a DAI systems' agents share, at least for those that can be divided into parcels for the agents to own. For example, we may allocate each agent a particular amount of raw material for a job, or allocate it a time slot for accessing a communication channel, its sonar, or a power supply. Though we may not need to worry about DAI agents seeking investment opportunities, we still need to ensure equity of distribution. Privatization is susceptible to problems arising from uncertainty (e.g., if we overestimate the amount of a resource, we may inadvertently assign ownership of a portion of it to two or more agents) and from the actions of uncontrollable and/or unpredictable agents that are not part of the DAI system. Also, some resources can't be split, and even for those that can be, there may be no way to enforce "property rights".

Mutual coercion mutually agreed upon. Hardin [1968] suggests that one of the only means for averting the tragedy of the commons is "mutual coercion mutually agreed upon", by which some individual freedom is traded for the greater good of the entire system. One way that seems to work for human systems is a progressive tax based on resource use—for example, parking meters (and fines for enforcement and if the users exceed the limit). By such means, there is a penalty for overusing the resource in proportion to the amount of use. It is difficult to see how this could be adapted for use in a DAI system, unless it is by the introduction of some sort of artificial pricing system. But unless the pricing system has real value for the agents and is universal for users of the resource, the scheme will fall apart. Another alternative is the creation of agencies for managing the resource, a kind of socialism in which the resource is still owned by all, but managed by something like a bureau [Hardin, 1977; Ostrom & Ostrom, 1977; Baden, 1977], with a mechanism by which the managers or bureaus are held responsible for the health of the resource.

For DAI systems, the role of "agencies" or "bureaus" can be filled by selecting one or more agents to control the resource while at the same time making that agent or set of agents answerable for its decisions to the entire DAI system or to its designers. Responsibility in human agencies is often by means of threats of removal of poor managers or of monetary or other punishment for poor performance. In DAI systems, it may be sufficient to give the controlling agent a high-priority goal to manage the resource effectively (according to some *a priori* metric). It is important, however, that the agent be responsible to the other agents using the resource. This can be implemented by giving the other agents the power to change managers as needed. An interesting approach along this line is taken by Cammarata and colleagues [Cammarata *et al.*, 1983] in the domain of air traffic control, where managers (planners) are chosen based on their properties and properties of the current situation; the resource managed in this situation is airspace. In domains where interactions with respect to a resource are less ephemeral, it may be more efficient to designate a single manager for the resource, changing the manager only if the other agents perceive that it is not performing well.

There are problems, however, with centralized management of group-owned common pool resources. Since it is a kind of multiagent planning, it is subject to the same limitations. However, here there may be a set of planners rather than just one, and the planner or set of planners is responsible to the other agents, in that they have the authority to replace the planner. This ameliorates the problem of selecting the right planner for the job and the problem of the planner having a personal stake in how the resource is used. Bureaus also suffer from problems of poorly estimating societal (i.e., system-wide) benefits and demand for the resource, lack of information about processes or the resource itself, and determination of an optimal level of the resource [Baden, 1977], all of which impact DAI as well as human management of common resources. Also, as Ostrom and Ostrom [1977] point out, if the agency's scope of control, in terms of users of the resource, is too narrow, then some users will be exempt from regulation, and the commons will be at risk. If the scope is too broad, then agents that are not actually users of the commons will have an inappropriate say in how it is used and possibly share in its costs and/or benefits. Shifting conditions and uncertainty will also undermine the efficacy of an agency's management of a resource [Ostrom & Ostrom, 1977].

Recommendations and Future Work

Distributed AI systems, like other collections of agents that share resources, run the risk of inadvertently destroying those resources through agents pursuing their own goals. This is especially true of the kinds of DAI systems that are the most useful, those that are fielded for actual tasks over a period of time outside of the laboratory.

In this paper, we have identified some of the characteristics of the agents, domains, and resources that predispose to the tragedy of the commons, and we have tried to lay some of the groundwork for pursuing solutions to the problem of managing common pool resources. It is a thorny problem, with no clear, foolproof solutions, but some guidelines and recommendations are possible. First, agents (or the DAI system as a whole) should be able to recognize when they are sharing resources with others. Second, all efforts should be made to decrease uncertainty, since it has the potential to undermine almost any solution to the problem. Third, agents need to communicate to coordinate their actions with respect to the commons. Fourth, if the DAI system shares resources with outside agents, then it (or its designers) should consider looking for alternative resources that are *not* shared; if this is impossible, then efforts should be made to coordinate with the other agents in managing the resource. Fifth, voluntary measures or conventions may be used as long as individual goals are subordinate to preserving the resource and uncertainty is low. Sixth, for some resources, privatization may be possible; if so, it offers a relatively clean solution to the problem. Finally, the system designers should consider mutual coercion, mutually agreed upon. Flexible mechanisms are needed by which DAI agents can create new management "agencies" (i.e., one or more of the agents acting as managers) for common pool resources. The other agents need the power to adjust the scope of the manager's control or change managers as needed, but the managers need the power to administer the resource. While this will not in itself avert every instance of the tragedy of the commons—there will still be the problems of uncertainty and resource users external to the system, for example—it is likely to be the one of the best solutions available.

Future work, both theoretical and experimental, is needed to determine which of these mechanisms are best for which DAI systems, and under what circumstances. It will also be important to investigate what role DAI systems can play as models of other systems with common pool resources. Used in this way, DAI systems can simulate the fate of a commons and can be valuable testbeds for potential solutions to the tragedy of the commons affecting other areas of interest to society, such as overfishing and extinction of species, destruction of tropical rainforests, and global warming.

We anticipate continuing our research on the management of common pool resources in DAI systems and also urge others to consider the tragedy of the commons. The problem of the commons is an important one, for in both human and DAI systems, as Hardin [1968] has said, "Freedom of the commons brings ruin to all."

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