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Groups of Agents with a Leader

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Abstract

We describe simulations of groups of agents that have to reach a target in a two dimensional environment, the performance criterion being the time taken by the last agent to reach the target. If the target is within a given distance from the agent, the agent moves towards the target; otherwise it moves randomly. The simulations contrast groups with and without a leader, where a leader is a member of the group which other members of the group follow as it moves through the environment. We investigate three factors that affect group performance: (1) group size; (2) the presence or absence of an individual agent with the ability to detect targets at a greater distance than those 'visible' to its companions; (3) the existence of a communication network among group members. The results show that, in groups without communication, leaders have a beneficial effect on group performance, especially in large groups and if the individual with better than average sensory capabilities is the leader of the group. However, in situations where group members can communicate, these results are reversed, with leaders being detrimental, rather than beneficial, to group performance

Keywords:
Agent Based Models, Leaders, Social Simulation, Social Structure, Communication Topologies

Introduction

1.1

What is a leader? A leader is an individual which tells other individuals what to do. Where there is no leader, the only way for a group of agents to accomplish a collective task is for each agent to act independently on the basis of the information available. Where there is a leader, the leader can indicate to the other agents of the group what they should do to solve the task. In the former case, social coordination is an emergent property of the behavior of individual agents; in the latter, at least to some extent, it is a result of the decisions of the individual agent which acts as leader. What difference does it make for a group of agents to have a leader?

1.2

Research in collective robotics (Drogoul, Tambe and Fukuda 1998; Parker, Schneider and Schultz 2005), swarm intelligence (Bonabeau, Dorigo, and Theraulaz 1999; Eberhart, Shi, and Kennedy 2001; Sahin and Spears 2005), and multi-agent systems (Gilbert and Doran 1994; Sichman, Conte, and Gilbert 1998; Wooldridge 2002; Gilbert and Troitzsch 2005) has mostly focused on homogeneous groups of agents in which all individuals have the same social role. Other work has investigated groups of agents in which different agents are dynamically assigned different sub-tasks, as the situation changes. In these studies, however, the dynamic assignment of different tasks is not a decision taken by one particular agent, the leader or chief of the group, but is itself an emerging property of group behavior (Lerman, Jones, Galstyan, and Mataric 2006). (For an agent-based model of work teams in which the project manager chooses the most appropriate team members, see Moreno, Valls, and Marin 2003.) Agent-based models have been used to investigate the dynamic emergence of opinion leaders or individuals who influence other individuals (e.g.,Anghel, Toroczkai, Bassler and Korniss 2004) and the possible advantages of the presence of leaders for resource sharing (Younger 2003). But, although some work has been dedicated to groups of agents which include a leader (e.g.,Murakami, Minami, Kawasoe and Ishida 2002; Jadbabaie, Lin and Morse 2003), in most cases formal and simulation models of social behavior and organization have emphasized the spontaneous emergence of socially coordinated behavior rather than leaders and centralized control. By contrast, groups of real organisms often display social hierarchies with some individuals acting as leaders or chiefs and other individuals as followers or subordinates. In lower organisms, such as insects, groups tend not to have leaders. Primates on the other hand often have complex social hierarchies (Kummer 1971). When a group of primates moves together in the environment, specific individuals play a more important role than others in the initiation of movement and in the choice of the direction in which the group has to move (Boinski and Garber 2000). Informal and formal social hierarchies are also a characteristic feature of human groups, so much so that there exists an entire academic discipline—political science— dedicated to social power in human societies.

1.3

The study of groups of agents with a leader could contribute not only to our understanding of human social phenomena but also to the development of teams of agents with practical applications. Today, practical applications of collective robotics are being actively explored in such diverse fields as agriculture, monitoring and surveillance, and entertainment. Other applications are likely to emerge in the near future. Although teams of agents that include individuals with different social roles are relatively complex to develop, it seems likely that for some tasks and applications, socially heterogeneous groups will provide new kinds of functionality and better performance than homogeneous groups.

1.4

In this paper we describe the results of very simple simulations illustrating how the presence or absence of a leader can affect a group of agents' ability to perform a collective task. We investigate three factors that affect group performance: (1) group size, (2) the presence or absence of an individual with the ability to detect targets at a greater distance than those "visible" to its companions, (3) communication among group members.

The simulation scenario

2.1

A group of agents has the task of reaching a target located in a two dimensional environment. The tasks is deemed to have been completed when all the agents reach the target. It is thus a collective task. Group performance is measured as the time taken by the last agent to arrive at the target. The environment is a grid of 50×50=2500 cells. The target occupies a single cell as do the individual agents. A simulation comprises 100 runs, with each run lasting until the last agent has reached the target. At the beginning of each run, the target and the agents are randomly positioned in the environment. At each time step, each agent moves to one of the four diagonally located cells surrounding the cell in which it is currently positioned. (Two or more agents can occupy the same cell.) Agent behavior is determined as follows. An agent is supposed to have sensory organs that can detect targets within 5 cells of its current location, i.e., if the target lies inside a square of 11×11 cells with the agent at the center of the square. When a agent perceives the target, it moves directly towards it, using the shortest path available. When the agent is unable to detect the target (i.e., the target is more than 5 cells away) it randomly chooses one the four diagonally located cells adjacent to its current cell and moves to the new cell. If the cell chosen is outside the wall encircling the environment, the agent remains in its current cell. Each run is divided into cycles or time units. In each cycle agents' positions are updated in random order.

Simulations

Groups without a leader

3.1

We establish a baseline by running simulations in which all agents have the same social role (i.e., there is no leader), and each agent moves through the environment based on its own perceptions. To investigate the role of group size we run separate simulations with groups of 10 and 50 agents, respectively. The results are shown in Table 1.

Table 1: Time (average number of time units) taken to reach the target by the first and the last agent in homogeneous groups of 10 and 50 agents (standard deviations in brackets)

Group size	First	Last
10	57 (103)	5427 (3660)
50	3 (5)	8244 (3658)

3.2 Table 1 shows that without a leader small groups perform better than large groups. Notice that the *first* agent to reach the target takes less time in large groups than in smaller ones. This is a question of simple probability. The higher the number of agents in the group the higher the probability that in any one cycle at least one agent will be within detection range of the target. However, the *last* agent to reach the target—our criterion for group performance—takes less time in small groups. The results in Table 1 refer to the case in which each agent starts from a randomly chosen location. However, the same results are obtained if all the agents start from the same location. In this case the difference between small and large groups is somewhat smaller.

Groups with a leader

3.3 Consider a group of agents in which one agent plays the role of "leader" and all remaining agents are "followers". In each cycle the leader moves first. Then the other agents follow, updating their positions in random order. The behavior of the leader is governed by the same rules as that of the agents in the previous simulation: if it cannot detect the target, it moves randomly; if it can, it moves directly to the target. However the rules for a follower are different. If it can detect the target, it goes directly to the target and ignores the leader. But if it can't, it moves in a direction which is halfway between (a) the direction it would have taken if it had chosen its direction randomly and (b) the current location of the leader. The results of the simulations with a leader are shown in Table 2.

Table 2: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with a leader

Group size	First	Last
10	654 (1431)	1800 (2172)
50	81 (468)	1984 (2770)

3.4 The results demonstrate that having a leader has a beneficial effect on group performance. Having a leader implies that followers tend to remain close to the leader and to explore the environment in a more aggregate way. This is beneficial because when the leader or one of the followers happens to discover the target, the other individuals in the group will also be near to the target. Without a leader the other individuals in the group will on average be further away from the target.

3.5 The beneficial effect of the presence of a leader is greater for large than for small groups. For groups of 50 agents with a leader the last agent reaches the target more than four times faster than in groups without a leader (cf. Table 1); in groups of 10 agents the leader improves performance by a factor of three. In Table 1 we saw that small groups without a leader have an advantage over larger groups. But the results in Table 2 show that the presence of a leader almost cancels out this advantage. What is crucial is that the presence of a leader allows the group to explore the environment in a more aggregate way. We observe that other rules favoring aggregate exploration might have the same effect. For instance, if each individual tends to remain close to other individuals (cf. the 'swarm' behavior of flocks of birds, schools of fish, and communities of social insects; cf.Bonabeau, Dorigo, and Theraulaz 1999; Krause and Ruxton 2002), this would be equally advantageous. In the next section we examine what happens when the leader has better sensory capabilities than followers. We will see that, in this case, the presence of a leader produces benefits that cannot be obtained in leaderless groups.

Groups of agents in which one agent has better sensory capabilities than the others

3.6 In the baseline simulations, all agents have the same sensory capabilities: they can only detect the target if it is within a maximum distance of 5 cells. The same is true for the simulations with a leader described in the preceding section: the leader influences the behavior of followers but has the same sensory capabilities as the other members of the group. We now provide one individual with better sensory capabilities than the others, allowing it to detect targets at a distance of 15 cells. Table 3 shows that in the absence of a leader the effects on group performance are marginal.

Table 3: Time taken to reach the target by the first and the last agent by groups of 10 and 50 agents without a leader and with one agent having strong sensory capabilities than the other agents

Group size	First	Last
10	43 (88)	5459 (3751)
50	3 (5)	8104 (3434)

3.7 However, if the individual with superior sensory capabilities is the leader, this is very advantageous for group performance (Table 4): the leader's special capabilities allow the group to reach the target far more rapidly than would occur in groups where all the agents have the same capabilities. Again, large groups benefit more than small ones. In groups of 50 agents, the time taken by the last individual to reach the target is five times less than in groups where all agents have the same capabilities. The latter groups in turn reach the target four times faster than groups with no leader at all (see previous section). Groups of 10 agents achieve a three-fold advantage.

3.8 Note that in this case "swarm behavior" is of little advantage to the group, which benefits only if the individual with superior sensory capabilities is also the leader of the group. Of course, it would be nice if all individuals in a group had the same superior sensory capabilities as the leader but in reality this is rare: in most situations cognitive resources tend to be scarce and unevenly distributed among individuals.

Table 4: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with a leader whose sensory capabilities are superior to those of followers

Group size	First	Last
10	467 (1093)	657 (1081)
50	40 (211)	398 (569)

3.9 In additional simulations, we investigate what happens when the group includes one individual with superior sensory capabilities but this individual is not the leader of the group. The results show that the performance of these groups is worse, not only than that of groups where the "superior" agent is also the leader, but even of groups with uniform capabilities (Table 5).

Table 5: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with a leader and with one agent (not the leader) with superior sensory capabilities

Group size	First	Last
10	305 (858)	1973 (2183)
50	40 (211)	2350 (3022)

In other words, an individual with superior sensory capabilities is useful to the group only if it is also the leader of the group.

Adding communication

3.10
In the simulations described so far, there is no communication among the members of the group. The only information guiding an agent's behavior is the information the agent extracts directly from the environment. Thus, if an agent cannot detect the target, it moves randomly. In what follows, we will describe simulations in which group members can communicate. An agent which knows the location of the target (because it can detect the target itself or because another agent has provided the information) informs the other agents so that they can move directly to the target.

3.11
We examine two types of communication. In the first type, agents can communicate independently of their spatial location. We examine three cases: (1) every agent can communicate with every other agent (all-to-all topology); (2) every agent can communicate with a single, special, agent which then relays the information to the other agents (star topology); (3) the agents form a "ring" and each agent communicates with its two adjacent agents (ring topology). Communication between agents is always two-way. However, if an agent knows the target location at time T, it will communicate this information to all communicatively linked agents at time step T+1.

3.12
The second type of communication is space-dependent. In this case, two agents can communicate only if the physical distance between them is less than 20 cells. An agent that knows the location of the target communicates this information to all other agents that are within this distance.

3.13
In what follows, we will describe the results obtained in groups of agents without a leader and in groups with a leader. In both cases we will consider space-independent communication first, and then space-dependent communication.

3.14
Groups with space-independent communication perform much better than groups without communication. Large groups perform better than small ones: as soon as one agent discovers the target it communicates the relevant information to the other agents which stop exploring the environment randomly and move directly to the target. Given that in large groups it takes less time for the first agent to discover the target, these groups outperform smaller ones.

Table 6: Time taken to reach the target by the first and the last agent in homogeneous groups of 10 and 50 agents without a leader and with communication: (a) all-to-all topology; (b) star topology; (c) ring topology

(a)

Group size	First	Last
10	57 (103)	95 (105)
50	3 (5)	45 (8)

(b)

Group size	First	Last
10	57 (103)	99 (105)
50	3 (5)	50 (8)

(c)

Group size	First	Last
10	57 (103)	107 (104)
50	3 (5)	91 (25)

3.15
The best results are obtained with an all-to-all topology, followed very closely by the star topology. The ring topology produces significantly poorer performance, especially with groups of 50 agents. With all-to-all communication it takes only one time step for all individuals to learn the location of the target as soon as one of them has discovered the target; with the star topology it takes two time steps, and only one time step if the agent which discovers the target is the agent at the center of the star. With the ring topology, the number of steps required for all agents to know the location of the target is half the number of individuals in the group. Hence, the advantage of the all-to-all and star topologies become progressively greater as the size of the group increases. One should consider, however, that the star topology has fewer communications links—and thus potentially lower costs—than the all-to-all topology. We further observe that it would be easy to improve the performance of the ring topology by adding a few long-range links, therefore transforming it into a small world topology.

3.16
The results of adding space-dependent communication to groups without a leader are shown in Table 7.

Table 7: Time taken to reach the target by the first and the last individual in groups of 10 and 50 agents without a leader and space-dependent communication

Group size	First	Last
10	57 (103)	720 (1184)
50	3 (5)	56 (10)

3.17
Predictably, space-dependent communication is less effective than space-independent communication. The effect varies as a function of group size. In groups of 50 individuals, there is only a small deterioration in performance compared to groups with space-independent communication. In groups of 10 individuals, however, space-limited communication results in much worse performance. The reason is that with space-dependent communication information takes longer to reach all the individuals in a group. Given an environment of a certain size, individuals in large groups tend to be closer to one another because of their greater density. As a result, the negative effects of space-dependent communication are limited. By contrast, small groups tend to be more dispersed and information takes longer to reach all the individuals in the group.

3.18
In the simulations described so far, we add communication to groups which do not have a leader. We now consider what happens when we provide communication to groups with a leader. As before, we will consider space-independent communication first, then space-dependent communication.

3.19 The more interesting result is that if the agents in a group can communicate with each other, the presence of a leader loses much of its importance and can even be detrimental to group performance. As we know, in the absence of communication, the presence of a leader is useful because it allows the group to explore the environment in a more aggregate way. This has benefits but also costs. Moving as a group is beneficial because when one individual discovers the target the other members of the group will be close by. But it also has costs: a closely aggregated group will explore the environment less widely than a more dispersed one. If the costs are to be less than the benefits, it is crucial that followers should not remain *too* close to their leader. If followers are too close, the group acts in effect as a single agent and usually takes a very long time to discover the target.

3.20 The addition of communication to groups with a leader has no effect on the cost of exploring the environment in an aggregate way but cancels its benefits (Table 8). As soon as one individual discovers the target, all the other individuals in the group will know its location and move directly to the target, the small differences in performance being due to differences in the communication topology. As already observed, the advantage of moving as a group is that the whole group is close to the target when it is detected for the first time. But in groups with communication all individuals reach the target rapidly, independently of their location. As a result, the presence of a leader has a negative impact on group performance. In a group of 50 individuals with a leader and all-to-all communication, the last individual to reach the target takes more than twice the time taken by the last individual in a group without a leader. In groups of 10 individuals, the time taken is more than six times as long. The results for star and ring topologies are very similar.

Table 8: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with a leader and space-independent all-to-all communication

Group size	First	Last
10	654 (1431)	679 (1426)
50	81 (468)	119 (464)

3.21 Let us now consider how the presence of an agent with superior sensory capabilities affects the performance of groups of communicating agents. First we will consider groups without a leader, then groups with a leader.

3.22 We have already seen (cf. Tables 1 and 3), that in the absence of communication, the performance of groups without a leader is not affected by the presence of an individual with superior sensory capabilities. Even if on average the individual with superior capabilities will discover the target before its companions, this does not translate into an advantage for the group. By contrast, in groups with communication, the presence of an individual with superior capabilities leads to better group performance, at least in groups of 10 individuals (Table 9). Not only does the individual with superior capabilities discover the target before its companions but it also communicates this information to the rest of the group (compare Table 9 with Table 6a). Therefore all the group benefits from its superior capabilities.

Table 9: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with communication, without a leader, and with one individual with better sensory capacities than the other individuals

Group size	First	Last
10	43 (88)	79 (89)
50	3 (5)	45 (8)

3.23 On the other hand, in groups with a leader, the presence of an individual with superior capabilities does not change the fact that the presence of a leader penalizes group performance (Table 10). This is true regardless of whether the superior individual is the leader or a follower. If it is the leader, group performance is better than when the leader has the same capabilities as its followers. If it is not the leader, group performance is even better. But in all cases the performance of groups with a leader is much worse than that of groups without. This effect is especially strong in groups of 10 agents. In sum, having a leader has a detrimental effect on performance in any group of agents in which there is communication.

Table 10: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with space-independent all-to-all communication (a) with a leader with superior sensory capabilities, and (b) with a leader and another individual with superior sensory capabilities.

(a)

Group size	First	Last
10	467 (1093)	489 (1086)
50	40 (210)	77 (206)

(b)

Group size	First	Last
10	305 (858)	331 (854)
50	40 (210)	77 (206)

3.24 We now turn to groups with a leader and space-dependent communication. In these groups, an individual that knows the location of the target will communicate this information to other individuals provided these other individuals are within a distance of 20 cells.

3.25 As we already know (cf. Table 7), small groups without a leader perform badly if the communication system is space-limited. This is because individuals in small groups are more dispersed than those in larger groups and space-dependent communication takes more time to reach them all. In our simulations, the presence of a leader implies that the group moves in a more spatially aggregated way. Therefore, in small groups with a leader, the individuals tend to be close to each other and even with space-limited communication information reaches all the individuals in the group very rapidly. In large groups, on the other hand, the presence of a leader either has no effect on performance or makes it worse. This is true regardless of whether communication in the group is space-dependent or space-independent (Table 11).

Table 11: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents with a space-dependent communication system and (a) a leader with the same sensory capabilities as the other members of the group; (b) a leader with better sensory capabilities than the other members of the group; (c) a leader and another individual with better sensory capabilities than the other members of the group

(a)

Group size	First	Last
10	654 (1431)	703 (1424)
50	81 (468)	129 (468)

(b)

Group size	**First**	**Last**
10	466 (1093)	513 (1087)
50	40 (211)	87 (217)

(c)

Group size	**First**	**Last**
10	305 (858)	364 (860)
50	40 (210)	86 (217)

3.26
Finally, we report the effect of adding an individual with superior sensory capabilities when the group has no leader and has space-limited communication (Table 12).

Table 12: Time taken to reach the target by the first and the last agent in groups of 10 and 50 agents, with space-dependent communication, no leader, and one individual with superior sensory capabilities

Group size	**First**	**Last**
10	43 (88)	646 (1175)
50	3 (5)	56 (10)

3.27
If we compare these results with those of Table 7, we see that the presence of an individual with better sensory capabilities but which is not the leader does not influence the performance of the group.

Discussion

4.1
We have described a set of simulations in which groups of agents have to reach a target located in a two-dimensional environment and the performance of the group is measured in terms of the time taken by the last individual in the group to reach the target. Each individual agent moves randomly until it is informed by its senses or by another individual about the target's location. At this point the individual takes the shortest path to the target. We were interested in contrasting two conditions: (1) all individuals have the same social role and each individual behaves autonomously on the basis of the information available to it; (2) the group includes a leader, that is, an individual who other individuals tend to follow as it moves through the environment. We have manipulated a number of variables that can have a role in determining group performance: group size; the presence or absence in the group of an individual (the leader or a follower) with the ability to detect targets at a greater distance than those detectable by other group members; the presence or absence of a communication network through which an individual that knows the location of the target can communicate this information to other individuals; the space-dependent or space-independent nature of the network topology.

4.2
Our main results can be summarized as follows. In the absence of a leader and without communication, small groups perform better than large ones. Large groups explore the environment more widely than smaller ones. As a result the first individual to discover the target takes less time than in a small group. But in small groups the last individual to discover and reach the target takes less time than in large groups. Given the collective nature of the task it is this time that determines the performance of the group.

4.3
In the absence of communication, the addition of a leader—an individual that can partially dictate the way the group moves in the environment—has a beneficial effect on group performance. The presence of a leader causes the group to explore the environment as a group, so that when one individual discovers the target the other individuals are close by. Hence, large groups benefit more than small ones.

4.4
The presence within the group of an individual with superior sensory capabilities (the ability to detect the target at a greater distance) has a beneficial effect on group performance only if the individual is the leader of the group. This is because the leader can literally lead the group to the target. On the other hand, if the individual with superior capabilities is not the leader of the group, the fact that it may discover the target before its companions does not benefit group performance.

4.5
The addition of a communication system allowing an individual that knows the location of the target to communicate this information to other individuals in the group, more or less reverses the results obtained without communication. With communication, large groups without a leader perform better than small groups. This is because the critical factor in groups with communication is the time taken for the first individual to discover the target: this individual will immediately communicate the information to the other individuals in the group. And, as we have already said, in large groups it takes less time for the first individual to discover the target than in small groups.

4.6
The presence of communication also affects the role played by leaders: in groups with communication the presence of a leader tends to be detrimental, rather than beneficial. Groups with a leader explore the environment in a more aggregate way. This implies that in these groups it takes longer for the first individual to discover the target, than in leaderless groups. And since small groups aggregated around a leader explore the environment less widely than large groups, the negative effects of the presence of a leader are greater for small groups than for large ones.

4.7
The presence of a leader penalizes the performance of groups in which the individuals communicate with each other even when one individual in the group has better sensory capabilities than other individuals. Groups with communication perform best when the individual with superior sensory capabilities is *not* the leader.

4.8
The presence of a leader has negative effects on group performance regardless of the topology of the communication network—though it is more detrimental with all-to-all than with space-dependent communication.

4.9
In our simulation, agents move randomly in a two-dimensional physical environment and they have to find a spatially located target. However, it is possible to generalize our scenario. Let us consider our two-dimensional search space as a particular example of an abstract search space with many dimensions. In this interpretation, the target represents the correct solution to some problem. The problem is a collective one because individual agents are rewarded only if all the agents find the solution. The agents' random movements in our two-dimensional space can be interpreted as possible solutions generated by the agents.

4.10
Applying this abstract interpretation, we conclude that in the absence of a leader or communication, small groups of agents outperform large ones in solving collective problems. However, groups with a leader perform better than groups without a leader, and the beneficial effects of the presence of a leader are greater for large than for small groups. This is because the presence of a leader orients the way the group searches for a solution: when one individual finds the solution, the others are already close to it. The same beneficial effect can also be obtained without a leader, for instance if each individual in the group tends to imitate other individuals (swarm behavior). However, the best results are obtained when the leader has a stronger problem solving capability than its followers. In this case the leader leads the entire group to the solution, thereby solving the collective problem. The presence of an individual with superior problem-solving capabilities who is not the leader has only a limited positive influence on group performance. To achieve superior performance, it is

necessary that the leader should be better at solving problems than other individuals in the group. The problem of how to select such a leader is one of the basic problems facing a democratic society. In his *Politics*, Aristotle (2000) writes that leaders should be individuals who "can predict with intelligence". But in actual human societies leaders are not always chosen on this basis.

4.11

With the emergence of communication, especially the kind of space-independent communication made possible by modern technology, leaders are no longer so important in determining a group's ability to solve collective problems. If any individual who finds the solution to a collective problem is able (and willing) to communicate the solution to all other individuals, the group can solve the problem very efficiently, even if there is no leader and all the members of the group have the same problem solving capabilities (though the presence of an individual with superior capabilities is helpful). In these circumstances, the presence of a leader tends to be detrimental, rather than beneficial, for group performance. This finding may have interesting implications for the future of human societies with well-developed space-independent systems of communication such as Internet.

4.12

Of course, our simulations are very simple, and it would be wrong to claim too much on the basis of the simulation results. We would therefore like to conclude this paper by mentioning some of the limitations of our simulations and indicating directions for future research.

4.13

Leadership has many different aspects and functions. We have defined a leader as an individual whose behavior tends to be imitated by followers. In this sense, leadership is a quantitative variable. In each cycle of our simulations, followers move in a direction which is exactly halfway between the direction they would have taken in the absence of the leader and the direction to which leader has moved. In this case, therefore, "leadership" has a value of 50%. If followers imitated the leader too closely, i.e., if the value of leadership were too close to 100%, this would have a detrimental effect: the group of agents would behave as if it were a single agent, i.e., the leader, and would no longer spread out to explore the space of possible solutions.

4.14

But leaders are not only individuals that are imitated by their followers. For example, they can also be individuals that tell other individuals what to do—and are obeyed—even if what followers have to do is different from what the leader does. Another difference between our simulations and the real world is the way agents cooperate. In the simulations, cooperation is guaranteed. Given that individual agents are only rewarded if all the agents in the group reach the target and that movement has no cost, there is no possibility of free riding. But if an agent can get some reward by individually reaching the target or movement has a cost, free riding is a real possibility: an agent may fail to communicate the location of the target to the other agents or may wait to learn the location of the target before moving. In these conditions, one of the role of the leader would be to discover and punish free riding.

4.15

Another problem is that the nature of leadership changes historically (Haas 2001). Our simulations show that to be beneficial to the group, it may be necessary for the leader to be superior in some critical way to other individuals in the group. Therefore one would expect that leaders are chosen because of their ability "to see at a greater distance" than the other members of the group. But in reality "chiefs come to power" (Earle 1997) in a variety of different ways, which do not always take this factor into account. Finally, our simulations consider a single level of social power, while human organizations and societies tend to have a hierarchy of levels, with leaders and sub-leaders. Another direction for future research is the identification of conditions favoring the emergence of hierarchical power structures. (For an agent-based model of emerging social complexity, cf.Doran and Palmer 1995).

Appendix: Description of the Algorithm

```
MAKE a grid world of 50×50 cells
SET group size (10 agents or 50 agents)
SET agents' attributes (viewing distance: 5 or 15 cells; presence/absence of leader; communication network: none, all to all, star, ring )
FOR runs = 1 to 100
        SET random seed
        CHOOSE  one cell randomly as target cell
        SET each agent's position randomly

        FOR ncycles = 1 to 20000
               FOR each agent
                      IF target in the agent's visual field or agent has been informed by another agent
                          about target's location
                      THEN move the agent towards the target by the shortest path
                               IF agent has communication links to other agents
                               THEN agent sends a message describing the targets  position to other agents
                                 ENDIF
                       ELSE
                               IF there is no leader or the agent is the leader
                               THEN move the agent to one of the four diagonally adjacent cells
                                    randomly selected
                                 ELSE move the agent to a diagonally adjacent cell in a direction midway
                                     between a randomly selected diagonally adjacent cell and the cell
                                     currently occupied by the leader
                                 ENDIF
                       ENDIF
               ENDFOR
        ENDFOR
ENDFOR
```

Web site: http://laral.istc.cnr.it/gigliotta/eca/ecaIndex.htm

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