Teamwork in Animals, Robots, and Humans

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I. Introduction

Teamwork is common in our own social interactions but is not restricted to humans. Animals, from ants to whales, may also work in teams. When part of certain multi-robot systems, robots may also use teamwork. However, do we really have the same notion of a team in each of these cases? Do the same definitions, concepts, and issues apply when considering these three seemingly disparate types of agents: animals, robots, and humans?

In this article, we consider what it means fundamentally to work as a team. Anderson and Franks (2001) recently redefined teamwork for animal societies and found that a definition developed primarily from studies of social insects also applied more generally to other social animals including vertebrates such as lions, hyenas, and whales. In other words, the crucial issues when a pod of humpback whales hunts cooperatively (Sharpe, 2000; Clapham, 2000) appear to be the very same as when a small group of army ants retrieves a prey item as a team (Franks, 1986, 1987; Franks *et al*., 1999, 2001). This, in itself, was a surprising result. What was more surprising, however, was that when Anderson and McMillan (200x) made a similar comparison between social insect teams and certain types of human teams (those that are self-organized), the same conclusions held. Despite the vast differences between humans and social insects, and the differences between their societies, certain aspects of their cooperative activity show strong commonalities. Taken together, these observations strongly suggest that there are certain underlying and possibly fundamental principles in the organization of work.

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The goals of this article are as follows. First, we will demonstrate that a single, generic definition of teamwork applies in vastly different social systems. Robots may also use teamwork when part of certain multi-robot systems. Second, we will specify how one recognizes and tests whether a particular instance of highly cooperative activity really is teamwork. How might we rigorously and objectively distinguish between teamwork and other closely related phenomena, such as groupwork? Third, we will broaden the scope from humans and non-human animals to a third major system of interacting "agents" in which teamwork is claimed—robotics. How do roboticists view teamwork in their systems, and, once again, are we dealing with the same issues and concepts of teamwork? Our fourth and final aim is to highlight and to clarify a number of common misconceptions about teamwork. Researchers in one field, based on the examples they usually encounter, may make certain claims about teams which, when one compares teams across fields, are not universally true. Thus, by discrediting some of these claims with revealing examples from other fields, we will draw out some of the truly generic features of teams.

Throughout, we clarify key concepts with illustrative examples. However, readers will notice a certain bias towards social insects. Teamwork has never been doubted in multirobot systems and human societies, whereas it has previously been disputed and dismissed in insect societies. A contributory factor is that so few examples were known. Even in Anderson and Franks' (2001) recent review, only a handful of candidate social insect teams were known (see also Anderson and McShea, 2001b). Now, however, we are in the position to illustrate a much larger, more significant, and informative collection of examples. Admittedly, our bias in favor of social insects also reflects our enthusiasm for these animals; they are a major research focus for both of us.

The organization of this chapter is as follows: First, we consider the structural organization of tasks, that is, a classification of task types (Section I). Then we examine teamwork in insect societies (Section II), in other (non-human) animal groups (Section III), in robotics (Section IV), and in humans (Section V). Section VI discusses team size, Section VII how one might test for teamwork, and Section VIII misconceptions about teamwork. Finally, there is a general discussion and conclusions followed by a summary (Sections IX and X).

A. Task Types

Before we can proceed, it is necessary to outline our general approach and perspective, which permits a meaningful comparison of work organization across vastly different systems. Our approach, first outlined in Ratnieks and Anderson (1999) and developed further in Anderson and Franks (2001) and Anderson *et al*. (2001), is to focus on the *structure* of the task itself, rather than focusing on the individuals tackling a task.

Tasks may sometimes be broken down into meaningful subunits or ''subtasks.'' For example, in the honey bee (*Apis mellifera*), nectar foragers collect nectar and transfer it to receiver bees back at the nest. The latter bees store the material in the comb (Seeley, 1995; Ratnieks and Anderson, 1999). Here there are two distinct subtasks, ''collection'' and ''storage,'' clearly delineated by the act of transfer. (This is a partitioned task; see later.) Other tasks have a different structure. For instance, when collectively retrieving a large prey item, *Formica* wood ants are notoriously uncoordinated; several ants may pull together in order to overcome frictional forces from over the ground, but they may, in fact, sometimes pull against each other (Sudd, 1963, 1965). Here there is no division of labor, and there are no subtasks—each individual has the same role, simply to pull. (This is a group task; see later.) It is from ideas such as these that a scheme of four fundamental task types based upon the interrelationship between subtask types was devised (Anderson and Franks, 2001; Anderson *et al*., 2001). The characteristic features of all four types are briefly outlined here, with a more detailed and definitional summary appearing in Table I.

TABLE I
CHARACTERISTICS OF THE FOUR TASK TYPES*

Task type	Number of individuals	Divided into subtasks?	Division of labor?	Concurrent activity necessary?	Subtask organization	Overall task complexity[c]
Individual	Single	No	No	No	—	Low
Group	Multiple	No	No	Yes	—	Medium
Partitioned	Multiple	Yes	Yes or No[a]	Yes or No[b]	Sequential	High
Team	Multiple	Yes	Yes	Yes	Concurrent	High

[a]Tasks can be partitioned without a division of labor (e.g., when an individual periodically switches between two or more of the subtasks) (Jeanne, 1986; Ratnieks and Anderson, 1999).

[b]Task partitioning requires concurrent activity when direct transfer occurs (i.e., when material is handed directly to another individual), but not necessarily when only indirect transfer (caching) is involved.

[c]Specified in detail in Anderson *et al.* (2001).

*This table defines the different task types; for instance, a team task requires two or more individuals (column 2) performing two or more subtasks (column 3) concurrently (columns 5 and 6).

After Anderson and Franks, 2001; Anderson *et al*., 2001.

1. *Individual task*. A task that a single individual can successfully complete without help from other individuals. For instance, for a lone hunter such as a domestic cat, capturing a mouse might represent an individual task, a task it can complete alone.
2. *Group task:* A task that necessarily requires multiple individuals to perform the same activity concurrently. Here there are no subtasks and there is no division of labor. In short, individuals must do the same thing at the same time or the task cannot be completed. For instance, *Myrmecocystus mimicus* honeypot ants perform highly stereotyped displays during territorial combats with neighboring colonies (Hölldobler, 1976). Workers convey the size and strength of their colony to their enemy by effectively forming a line of displaying ants along the boundary. This colony-strength (honest) signal only functions with the concurrent action of multiple individuals.
3. *Partitioned task:* A task that is split into two or more subtasks that are organized sequentially (Jeanne, 1986; reviewed in Ratnieks and Anderson, 1999; Anderson and Ratnieks, 2000). Nectar ‘‘collection’’ (subtask 1) and ‘‘storage’’ (subtask 2) in *A. mellifera* are two such examples. Partitioned tasks often take the form of some material or product that is passed from individual to individual (or even to some group) in a relay fashion. These task types are particularly easy to divide into subtasks, as it is the very act of transfer that delineates them.
4. *Team task:* A task that necessarily requires multiple individuals to perform different subtasks concurrently (Anderson and Franks, 2001). That is, there is a crucial division of labor and crucial concurrency. In short, *different individuals* must do *different things* at the *same time* or the task cannot be completed. For example, in the ant *Pheidole pallidula*, a polymorphic species that has both majors and minors, intruders are killed using teamwork. A group of workers will immobilize or ‘‘pin down’’ the intruder until a major arrives and decapitates it (Detrain and Pasteels, 1992). In this example, the task, ‘‘kill the intruder,’’ involves the following two subtasks: ‘‘immobilize the intruder,’’ a group subtask (that is, a subtask that is like a group task) and ‘‘decapitate the intruder,’’ an individual subtask (a subtask that is effectively an individual task). Only when both subtasks are performed concurrently can the task be completed; hence, it is a team task.

By focusing on the structure of the tasks, rather than on the individuals (or ''agents'') who tackle them and the cognitive abilities required to complete each subtask, we have created a common framework with which we can make comparisons across systems. We thus focus solely on the cooperative behavior and the interdependencies among individuals' contributions. Based upon a task's structural organization, it would then be possible to use the metric detailed in Anderson *et al.* (2001) to quantify a task's complexity. This potentially allows one, for instance, to rank different tasks from different systems objectively, to correlate a particular task's complexity with organization size or evolutionary history, or to follow how a particular task is sometimes tackled in a more complex, collaborative manner than at other times.

The above approach works on one level, task structure per se, and is individual independent. However, we may also wish to consider how a *particular* set of individuals must work to complete the task. That is, what may represent a difficult team task for one set of individuals—for example, a group of ants—may represent an easy individual task for an animal such as a human. Therefore, suggesting that a set of individuals can complete a certain task *only* in a certain way (e.g., as a team) is only meaningful and valid with regard to the constraints of the individuals tackling it. These issues, that the same task may represent a different task type to different individuals, and that a task may be tackled in one way at some times and in a different manner at other times, are discussed later (Section IX).

II. Social Insect Teams

In this section, we will first outline the reason Anderson and Franks (2001) felt it necessary to redefine social insect teams, which had been dismissed in all but a tiny minority of insect societies. This also introduces a number of key issues and insights about teamwork. This discussion is followed by a detailed examination of proposed social insect teams.

A. Why Redefine Teams?

In their important and highly influential monograph *Caste and Ecology in the Social Insects*, Oster and Wilson (1978, p. 151) include a three-paragraph subsection entitled ''*The nonexistence of teams*.'' We quote their text in full, italicizing two sentences of particular importance.

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> The relation of the members of an insect society to one another can be characterized as one of impersonal intimacy. With the exception of the dominance orders of primitively organized forms such as paper wasps and bumble bees, eusocial insects do not appear to recognize one another as individuals. Their classificatory ability is limited to the discrimination of nestmates from aliens, members of one caste as opposed to another, and the various growth stages among immature nestmates.
>
> *A consequence of this lower grade of discrimination is that members of colonies do not form cliques and teams*. Groups assemble to catch prey, excavate soil, and other functions requiring mass action; and odor trails and other sophisticated techniques have evolved that permit the rapid recruitment of nestmates to the work sites. But the participants are entirely changeable. *There is no evidence that they come and go as teams*.
>
> The lack of team organization is not necessarily the outcome of the limited brain power of social insects. It can be shown that at a very general level processes are less efficient when conducted by redundant teams than when conducted with redundant parts not organized into teams. This disparity can be overcome or reversed, as in fact it is in human beings, only if the degree of coordination among its members of the teams or between the teams is sufficiently great to compensate for the shortcomings inherent in the system redundancy.

We agree with all of this material except, crucially, the two italicized sentences. Insect societies are certainly a case of impersonal intimacy, and after twenty-five further years of research there is very little evidence that social insects can recognize each other as individuals (but see Tibbetts, 2002). Oster and Wilson, however, suggest that this is a necessary requirement for teamwork (the first italicized sentence). But why should this be? Suppose you are tying a parcel with string and need help. You ask the nearest person to put their finger on the point to be tied while you tie a bow. The task is completed and the person leaves. It is not necessary for you to know the person's name, or to recognize them during the operation or in the future. All that matters is that you coordinate your respective subtasks, ''putting finger on point'' and ''tying the bow,'' in the appropriate manner to complete the task.

As Oster and Wilson indicate in the second and third paragraphs, this is exactly the way that insect societies operate. They are inherently redundant, but that is their secret to success. Let us suppose that in our *Pheidole pallidula* example above, a group of minors have pinned down an intruder. A major that has been recruited, or happens to come across such an individual, does not need to recognize those ants holding the intruder down. All it must do is recognize that this is an immobilized intruder and perform the correct action: decapitate the individual. Thus, the sentence ''But the participants are entirely interchangeable'' is significant. This is exactly why such teamwork, and other coordinated activity in insect societies, is so adaptive. They do not need to work with certain individuals; anyone in the vicinity who has the ability to perform the required subtask(s) will suffice. Groups of individuals that came and went as a team would seem to be maladaptive. Any member that was lost would mean the functional demise of the whole team until a specific replacement could be found.

Twelve years after the publication of this monograph, Hölldobler and Wilson (1990) published their Pulitzer prize-winning book *The Ants*. By this time, the concept of teams, which had now become accepted to some degree, had changed significantly.

> Until recently, there has been no evidence for the existence of teams, which can be defined as members of different castes that come together for highly coordinated activity in the performance of a particular task. A team would not consist of particular ants, but rather of interchangeable members of particular castes…An exceptional case of team organization has been reported by Franks (1986) in the group retrieval of prey by *Eciton burchelli*…Teamwork needs closer study in *Eciton* and other ant species that employ group transport… (Hölldobler and Wilson, 1990, p. 343).

This issue of redundancy had been clearly recognized and addressed. However, in our minds, this definition is still overly restrictive in that it specifies that members of different castes must cooperate in a team. This has two important implications: (1) Teams could not occur in societies with monomorphic workers, and (2) even in a polymorphic society, there must be a mix of castes.

Can teams occur in monomorphic societies? Yes. Your parcel-tying helper could help you with your task, even if she were your clone. Our examples of social insect teams (detailed below) in *Aphaenogaster, Leptothorax, Myrmicaria, Protomognathus*, and *Apis*—all monomorphic genera (Oster and Wilson, 1978)—each involving similar-sized and similar-skilled individuals, illustrate this same point.

Must teams involve a mix of castes? No. Such a restriction would mean that a high school baseball team was not a team unless it contained a specialized pitcher, catcher, and so on. This is clearly not the case. A professional team on the other hand will likely contain such specialists because they will tend to enhance team performance. Similarly, in insect societies, natural selection favors certain castes specializing in certain subtasks in some situations (as in *Pheidole pallidula*, in which only the majors are capable of decapitation); but as an abstract concept—''team''—interindividual differences are not strictly necessary. An additional complication with Oster and Wilson's (1978) implication here is that species such as *Dorylus* driver ants, which have continuous size variation rather than discrete castes, would be difficult or impossible to classify as a team. How does one distinguish ''particular castes'' here? As we argue below (originally in Franks *et al*., 1999, 2001), *Dorylus* workers do sometimes work as a team.

If we have labored these two points, it is for an important reason: Under Anderson and Franks' (2001) definition, a team is simply the set of individuals that tackles a team task. There are no further assumptions or restrictions about caste, individual recognition, or other aspects of team membership.

In the following subsections, we review the existence of teams in insect societies. Although Anderson and Franks (2001) attempted such a review for social insects while redefining what it meant to work as a team, only very few examples were known then. Here, we list many new examples and demonstrate that such highly collaborative activity may be more widespread than originally thought. We also take this opportunity to include greater detail about some of these examples than is standard. This is because some of the literature is fragmented, sometimes old (dating to 1879 in one case), and can be very hard to track down.

B. *OECOPHYLLA*

There are two living species of *Oecophylla* ants, *O. longinoda*, which is found in Africa, and *O. smaragdina*, which ranges from India to Australia (Hölldobler and Wilson, 1983). These ants are known colloquially as weaver ants because they live in trees and bind or ''weave'' living leaves together to form their nests (Hölldobler and Wilson, 1977, 1983, 1990; Fig. 1a).

To achieve this complex task, it seems that three subtasks are needed. First, ants must ''pull the leaves together'' (subtask 1). This is easier said than done. If the distance between the two leaves is small, a single ant may be able to bridge the gap and start pulling. If this is the case, it may be that many workers will line up in parallel, a group task, and pull together. However, usually the gaps are much larger, several ant lengths or more, and so the ants form a striking structure, a pulling chain (a type of ''self-assemblage''; Anderson *et al*., 2002). A pulling chain is a chain of ants, each ant using their mandibles to hold onto the petiole or ''waist'' of the ant in front. While the first ant holds onto the leaf to be pulled, the last ant in the chain uses its tarsal claws to hook onto the other leaf. As it walks backward, it closes the gap so that the feet of the ant in front reach the leaf and hook on. This contraction of the chain closes the gap. Once the gap is closed, many workers then hold the leaves in place. As such, it is reasonable to consider this first subtask a group subtask.

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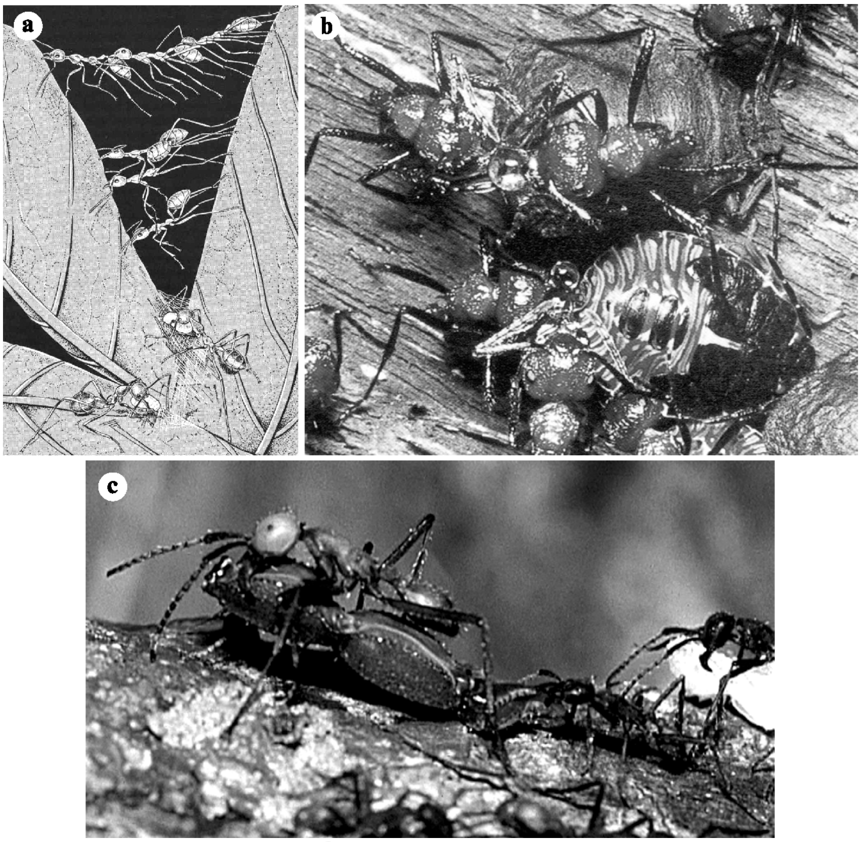

FIG. 1. a. *Oecophylla smaragdina* workers constructing a nest using teamwork (copyright Turid Höldobler-Forsyth, with permission). b. *Myrmicaria opaciventris* ants stimulate a *Caternautellia rugosa* nymph for honeydew (courtesy Alain Dejean, with permission). (See Section II.C.) c. Two *Eciton burchelli* ants, one sub-major (leading) and one minor (following), act as a team to retrieve part of a scorpion's tail (courtesy Nigel R. Franks).

While the leaves are being held together, the second main subtask, glueing the leaves together, must be performed. However, this too is a sophisticated behavior, a team subtask in itself. To glue the seam together, one worker will take one of the colony's own larvae and move it over the area to be glued while gently squeezing it (subtask 2). Such squeezing stimulates the larva to produce silk (subtask 3). In most ants, such silk would be used by a larva to spin its own cocoon; in *Oecophylla*, this silk now functions as glue.

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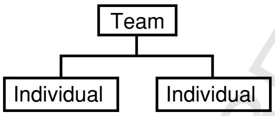
It is clear that *Oecophylla* appear to use highly sophisticated teamwork to form their nests. A pulling chain is used to bring the leaves together, usually a group subtask, while at the same time, they must be bonded using larval silk. This latter component is a team in itself—a team within a team—in which a larva produces the glue, an individual subtask, while the worker moves this living ''glue-gun'' over the area to be glued, another individual subtask (Table II; Anderson *et al*., 2001). All three components must be performed simultaneously for the task to be completed.

C. *MYRMICARIA*

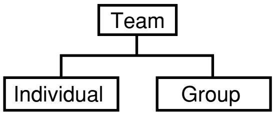
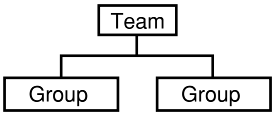
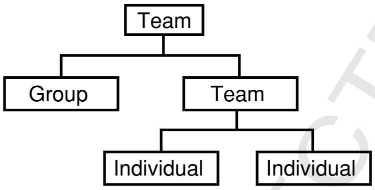
Many species of ants protect and tend to other insects—for example, aphids—in order to collect honeydew, the excess sugar-laden plant sap that the insects have tapped from the plant (Wheeler, 1910; Beattie, 1985; Hölldobler and Wilson, 1990). One such example, one that seems to involve teamwork, centers on the tending of the heteropteran *Caternautellia rugosa* (Fig. 1b). When a large ant such as a *Camponotus brutus* worker tends to one of these nymphs, the ant can carry out all the attendant tasks, including stimulating the nymph's dorsal glands while collecting the honeydew from the nymph's anus, by itself. For smaller ants, such as *Myrmicaria opaciventris* (Dejean *et al*., 2000; A. Dejean, personal communication), these two subtasks, ''stimulation'' and ''collection,'' must

TABLE II
TASK STRUCTURE OF SOME PROPOSED SOCIAL INSECT TEAMS*

Task structure and example	Task and subtasks
	$\mathbf{T} = \mathbf{I_1} + \mathbf{I_2}$
Aphaenogaster foraging from plants	T = Obtain capsule from plant; I_1 = Gnaw peduncle; I_2 = Twist capsule
Dorylus and *Eciton* prey retrieval (when there is a single follower)	T = Retrieve prey; I_1 = Front-running; I_2 = Following
Myrmicaria honeydew collection (with several worker stimulating nymph's dorsal glands)	T = Collect honeydew; I_1 = Collect honeydew; I_2 = Stimulate dorsal glands
Pheidole militicida seed opening	T = Open seed; I_1 = Hold seed; I_2 = Gnaw end of seed
Protomognathus (=*Harpagoxenus*) *americanus* and *Leptothorax* (=*Myrafant*) *duloticus* slave raids	T = Steal brood; I_1 = Guard entrance; I_2 = Capture brood

(*continues*)

TABLE II (*continued*)

	$\mathbf{T = I + G}$
Apis social encapsulation	T = Encapsulate beetles; I or G = Guard beetle; G or I = Build propolis corral
Dorylus and *Eciton* prey retrieval (when there is group of followers)	T = Retrieve prey; I = Front-running; G = Following
Myrmicaria honeydew collection (with several worker stimulating nymph's dorsal glands)	T = Collect honeydew; I = Collect honeydew; G = Stimulate dorsal glands
Pheidole and *Pheidologeton silenus* intruder decapitation	T = Kill the intruder; I = Decapitate the intruder; G = Immobilize the intruder
	$\mathbf{T = G_1 + G_2}$
Apis social encapsulation	T = Encapsulate beetles; G_1 = Guard beetle; G_2 = Build propolis corral
Pheidologeton diversus predation	T = Overcome prey; G_1 = Immobilize prey; G_2 = Kill prey
	$\mathbf{T_1 = G + T_2}$**, where** $\mathbf{T_2 = I_1 + I_2}$
Oecophylla nest construction	T_1 = Build nest; G = Pull leaves together; T_2 = Glue leaves together; I_1 = Move larva over seam; I_2 = Produce silk

*The hierarchical structures of the tasks are shown in the first column with each box representing a task or subtask. The particular tasks and subtasks are detailed more explicitly in the second column; T,I, and G represent team, individual and group (sub)tasks respectively. Subscripts are used when there is more than one (sub)task of the same type.

be performed by at least two individuals working concurrently, one or more stimulating the nymph while the other(s) collect(s) the honeydew. In the words of Dejean and his colleagues (2000: p. 450), "one to three workers waited for the honeydew secretion while others moved to the nymph's side or even climbed onto their bodies in order to palpate the dorsal glands.'' Thus, it seems that the *Myrmicaria* ants can only achieve the goal, to collect the honeydew, while working as a team.

D. *ECITON* AND *DORYLUS*

Prey retrieval by *Eciton burchelli* army ants (Franks, 1986, 1987) was the first accepted example of a social insect team (Section II.A; Anderson and Franks, 2001). In these teams, there are two subtasks—front running, involving a single ant at the front carrying the prey, and following, involving one or more ants, also carrying the prey but from the rear. The role of the front-runner is to get the prey item moving. As larger individuals achieve this more easily, it is perhaps not surprising that front-runners tend to be submajors. Submajors are rare in *Eciton* colonies (they make up just 3% of the workforce), but they represent 25% of all individuals—that is, porters—involved in prey retrieval (Franks, 1986, 1989). This more inclusive term is needed because it is individuals working alone who often transport prey items, not groups or teams. Once a submajor starts moving the prey item along the foraging column, other individuals join in and help. Sometimes there is just a single follower (Fig. 1c). At other times, several individuals, usually smaller ones, may help.

At first sight, the distinction between the two subtasks, front-running and following, might seem trivial. To show that it is not, consider prey retrieval groups, such as those in *Formica* wood ants (mentioned earlier). These ill-coordinated groups are notoriously inefficient, with different ants trying to take the lead (Sudd, 1963, 1965). However, army ants straddle the items they carry and both front-runners and followers face in the same direction. This means that the front-runner remains the front-runner and all of the ants work well together. In principle, two army ants might straddle the same item but face and pull in opposite directions, but this is never observed. This implies that the group has a distinct structure in which cooperation is maximized by a simple division of labor between the one at the front and the one or more at the rear (Anderson and Franks, 2001). Moreover, given the distribution of castes in the foraging column—that is, the individuals available to form the team—(Franks *et al*., 2001) found that the front-runner was especially large and the followers were especially small. In short, they have a particularly skewed distribution of team members. Such teamwork is not restricted to *Eciton*. These army ants, which live only in Central and South America, have an ecological counterpart, *Dorylus*, in Africa. *Dorylus* have a similar prey retrieval team structure to *Eciton*. One difference though is that *Dorylus* do not have discrete castes, but vary in size continuously across a very broad range. The same structure is also found: (1) single front-runners and one or more followers, and (2) especially large front-runners and especially small followers are also found (Franks *et al*., 2001).

The evidence that such a defined team structure in *Eciton* (Franks, 1986, 1987) and *Dorylus* (Franks *et al*., 1999) has a very important consequence: The teams are ''superefficient.'' In general, we might define superefficiency as *N* individuals completing a task more than *N* times faster or more efficiently than one individual (Franks, 1986; Balch and Arkin 1994; Balch *et al*., 1995). In short, superefficiency is a case of the ''whole being more than the sum of the parts.'' However, such is the effect in these ants that an item carried by a team cannot be divided up in any way so that all of the fragments can be carried away by the original team members. Franks (1986) suggests that the reason for this group-level property is that rotational forces disappear. Anyone who has carried a long plank of wood or a ladder by themselves will understand. Either it involves a careful balancing act, or it drags on the floor, making it harder to move. Compare that to how much easier it is when another person holds the end of the item. This does not necessarily arise from a sharing of the weight per se, although that will certainly help. Even if the helper simply stops the item from rotating and dragging, it makes moving the item far easier. Similar principles apply to team transport in army ants, which Franks *et al*. (2001) liken to a penny-farthing bicycle—an old bicycle which has a very large wheel at the front and a tiny wheel at the rear.

The analogy with a penny-farthing bicycle reveals how a team of two can be more than the sum of its parts. The tiny castor-like rear wheel on a penny-farthing bicycle transforms the properties of the machine out of all proportion to its size. Similarly, the synergism between a large ant and a small one in a team boosts the performance of both—again, because rotational forces are balanced and disappear.

E. *Apis*

Teamwork is not confined to ants. The following example comes from the Cape honey bee (*Apis mellifera capensis*), a species native to South Africa. Honey bee colonies may become infested by hundreds of small hive beetles (*Aethina tumida*). These small round beetles, each about half the size of a bee, have the ability to withdraw their legs and head into their tough ''shell.'' Hence, the bees have a hard time getting rid of them, especially as the beetles may hide in cracks in the nest. However, the bees have evolved a rather impressive way of dealing with them: They imprison them in sticky corrals, a behavior which has been termed ''social encapsulation'' (Neumann *et al*., 2001a,b). The bees use propolis, a sticky tree resin that the workers usually collect to seal cracks in the nest, to make a prison around the beetles. Some of these prisons completely seal their captives inside.

Construction can take up to four days and seal in a single individual or as many as two hundred beetles (Neumann *et al*., 2001a,b). The key point, however, is that the bees use teamwork to achieve this; while some bees make the prison, others guard the beetles and stop them from escaping (Neumann *et al*., 2001a,b; Ratnieks, 2001; Randerson, 2001). Both guarding and building may be individual or group subtasks, and all four combinations have been observed (P. Neumann, personal communication).

This behavior serves at least two purposes. First, it confines the beetles and can prevent them from reproducing, a particular problem because the beetles can be very fecund (Lundie 1940, cited in Neumann *et al*., 2001a). Second, if the infestation is very high and the best strategy for the colony is to abscond (desert the nest and start a new parasite-free home elsewhere), such teamwork can give the colony time to prepare for its departure. Interestingly, this teamwork is only seen in the South African race of the honey bee; other races do not appear to have evolved this shrewd strategy, and so infestations are more of a problem.

Ratnieks (2001) suggests that this teamwork is a social analogue of anti-parasite defense in multicellular organisms; that is, the host organism (read colony) uses special blood cells (cf. bees and propolis) to engulf or encyst (encapsulate) parasitic larvae that manage to elude the host's primary defenses.

F. *Protomognathus* and *Leptothorax* Slave-Making Ants

Of the ten thousand or so known ant species, only a tiny minority, about fifty species, are slave-makers (D'Ettorre and Heinze, 2001). Slave-makers are ants that raid the nests of other ant species and steal their brood. These stolen brood eclose into workers that essentially become domestic slaves for the colony. Interestingly, two of these slave-maker species hint at teamwork.

During a raid, host workers tend to grab their brood and flee the nest. However, in the slave-maker species *Protomognathus* (=*Harpagoxenus*) *americanus* and *Leptothorax* (=*Myrafant*) *duloticus*, a member of the raiding party acts as a guard at the nest entrance (Alloway, 1979; Foitzik *et al*., 2001). The guard prevents host workers from escaping with brood, thus ensuring there is brood to steal while other ants from the slave-making nest steal the brood. Structurally, this is a team task, "steal brood," with two individual subtasks—"guard entrance" and "capture brood."

G. *PHEIDOLE*

The *Pheidole pallidula* example discussed earlier is not the only instance of teamwork (*sensu stricto* Anderson and Franks, 2001) in this genus. Wilson and Hölldobler (1985, p. 18) describe very similar behavior in *P. embolopyx*: ''The minors seized the legs and spread-eagled enemy worker ants, while the majors attacked the body directly and were more effective at cutting them into pieces.'' And, in yet another species, ''Worker *P. punctulata* were seen holding down an [*Oecophylla*] *longinoda* worker while their soldiers 'jointed' [i.e., chopped into pieces] its limbs and body with their mandibles'' (Way, 1953, p. 681). (See Eisner *et al*., 1976, for a possible parallel among termites.) From these two vague descriptions, it is not possible to tell whether the cutting (or ''jointing'') subtask involves one or more majors acting simultaneously; that is, whether it is an individual or group subtask. More detailed descriptions are clearly needed.

In *P. militicida*, teamwork appears to serve a different purpose.

> The minors open the seeds of the [*Tridens*] *pulchellus* and *desvauxii* by gnawing at the pointed end of the seed. Sometimes the seed is held by one minor and gnawed open by another, but a more common method involves only one minor, who places the blunt end of the seed on the floor of the nest and, with the seed held in a vertical position gnaws at its pointed end (Creighton and Creighton, 1959, p. 7).

This is a perfect example of a task that is sometimes tackled by teams, with one worker ''holding'' and another ''gnawing,'' and sometimes by individuals, when one worker holds and gnaws simultaneously. This aspect, that a task may be of a different task type depending upon which animals are working on it, is covered in detail later (Section VIII).

H. *PHEIDOLOGETON*

The following, a rather anecdotal example of prey capture and dismemberment in *Pheidologeton silenus* ants, is similar to that of *Pheidole*: ''Minors pinned down prey, which were then torn apart by the mandibles of both minors and non-minors…(C. Kugler, 1978, personal communication)'' (Moffett, 1988, p. 359). From this scant description, the task structure is not entirely clear. However, like army ants, *P. silenus* is a group hunter with column and swarm raids. It is likely that both ''minors pin down prey'' and ''minors and majors tear apart prey'' are group subtasks, with the latter subtask involving a mix of castes. Moffett's (1987) account is also suggestive of such a scenario in *P. diversus*. In both species, it cannot be ruled out that the latter subtask could be conducted as an individual subtask by a media (an intermediate-sized ant) or major. However, more detailed observations and descriptions are needed to further categorize and analyze the task structure.

A description that exactly mirrors that of the *Pheidole*, hinting strongly that teams do exist in this genus, is the following:

> . . .when a hapless Malaysian *Diacamma* ant blunders directly into the midst of the marauder's [*Pheidologeton diversus*] trail, agile minors push forward to pin it to the ground. . .With the adversary defenseless, a major arrives and kills it with repeated crushing blows (Moffett, 1986, p. 286).

I. *Aphaenogaster*

An old reference that hints at another team task, but unfortunately whose text is so vague that it is neither clear which *Aphaenogaster* ant species or plant (shepherd's purse, *Capsella bursa-pastoris*, or chickweek, *Alsine media*) is being referred to, is the following. These ants climb plants to tear off green fruits to take back to the nest. This can be an individual task—an ant may ''seize the peduncle of the [shepherd's purse] capsule between its mandibles and, fixing its hind legs firmly as a pivot, twist the peduncle round and round until it is broken off'' (Heim, 1898, p. 414), but these ants may also sometimes work as teams involving two individual subtasks.

> We may frequently see two ants combine for the purpose of breaking the peduncle of a capsule. While one is gnawing the peduncle the other will twist it off; but it seems that their mandibles are never strong enough to sever the peduncle by cutting alone (Heim, 1898, p. 414).

J. A Cautionary Note

When ascertaining whether an insect society, or indeed any society, employs teamwork, we must be cautious; just because a description appears to be of a team task, it is not necessarily so. For example, Hogue (1972, p. 95) states, ''A major worker of [*Eciton*] *hamatum* locked onto its prey with its large mandibles. Workers this size restrain the prey while smaller individuals cut it to pieces.'' At first sight, this seems remarkably similar to some of our previous examples. However, Nigel Franks, having spent many years studying army ants in the tropics, believes that this behavior probably does not occur and is not indicative of a team. Similarly, the seed harvester ant *Pogonomyrmex barbatus* clears roadways free of plants leading from its nest and the disk around the nest itself by cutting them down. McCook (1879, p. 23; McCook, 1909, Fig. 35) cites occasional division of labor in this operation: "In two or three cases there appeared to be a division of labor; that is to say, while the cutter at the roots kept on with her work, another climbed the grass blade and applied the power at the opposite end of the lever. This position may have been quite accidental, but it certainly had the appearance of a voluntary co-operation." We find it hard to believe this in fact was a deliberate act and that two were cooperating in any meaningful sense.

As may be obvious from the previous subsections, many of the data and observations are rather anecdotal and have not been collected with such a perspective in mind (excepting *Apis, Dorylus, Eciton*, and *Oecophylla*). Thus the crucial detail that would discern which subtasks exist is missing. This is especially true of old references, as in McCook (1879, 1909) above, in which researchers tended to anthropomorphize greatly. In essence, they were seeking to ascribe human-like behavior and qualities to social insects. The crucial issue of how we should rigorously and objectively test for teamwork is addressed in Section VII.

III. Other Animal Teams

Cooperative hunting, in which several individuals work together to capture a prey that is usually then shared, occurs in a variety of vertebrate animal societies (reviewed in Ellis *et al*., 1983; Hector, 1986; and Bednarz, 1988, for raptors; and in Dugatkin, 1997, more generally; see also Boesch, 1994). Note that cooperative hunting does not necessarily involve a division of labor and therefore might only classify as groupwork. The following, however, do suggest a definite and necessary division of labor among concurrently-acting individuals, and hence may be considered examples of teams. But more detailed, dedicated experiments (as outlined in Section VII) are necessary before their status as true teams can be confirmed.

A. Birds

In African crowned eagles (*Spizaetus coronatus*) studied in Kibale Forest, Uganda, one bird will distract its prey (various species of monkeys) by flying in the midst of a monkey troop or sitting on a prominent perch where it is easily seen (Leland and Struhsaker, 1993). While most of the members of the troop flee, male monkeys will often jump up and down, vocalize, and perform other threatening displays. It is at this point, while certain males are preoccupied in display, that the bird's mate swoops down and attempts to capture one of these males. The two subtasks thus appear to be ''distraction'' and ''prey capture,'' and each is an individual subtask.

Whereas African crowned eagles employ a distract-and-ambush strategy, other birds employ a slightly different strategy—flush-and-ambush (Bednarz, 1988), in which one or more birds flush prey into the open where they are captured more easily by other team members. Aplomado falcons (*Falco femoralis*), which also hunt in pairs, are a case in point. Hector (1986, p. 251) states, ''When attacking prey in trees, females tended to fly close to the ground then ascend abruptly into the inner branches. At this point, prey species, [3 species of dove], quickly took flight. The male falcons then dove and attempted mid-air captures. In ensuing chases, females left cover and followed the fleeing prey while males attacked with repeated dives and ascents.'' These were probably not chance behavioral differences between the males and females because ''different pairs consistently showed the same division of labor in hunts'' (Hector, 1986, p. 254).

Galapagos hawks (*Buteo galapagoensis*) and Harris hawks (*Parabuteo unicinctus*) exhibit similar behavior, but the attack may come from one or two individuals and the flushing is performed by a group (Bednarz, 1988; Faaborg and Bednarz, 1990). For instance, when Harris hawks are chasing black-tailed jackrabbits (*Lepus californicus*) and desert cottontails (*Sylvilagus auduboni*), the prey may seek refuge from its group of attackers in a bush. While the hawks surround the bush, one or two birds flushed the prey from the bush, where it is then pounced upon by the waiting teammates. Here then, one subtask, ''surrounding bush,'' is most often a group subtask whereas the ''flushing prey'' subtask may be an individual or sometimes a group subtask (Bednarz, 1988).

B. Cetaceans

In the ocean, the problem of catching prey is often not flushing it from hiding but concentrating it to a sufficiently high density so that the capture probability is significantly raised. When Alaskan humpback whales (*Megaptera novaengliae*) hunt Pacific herring (*Clupea pallasi*), they appear to work as a team in which there are two subtasks: prey herding (a group subtask) and bubble blowing (an individual subtask) (Ingebrigtsen, 1929; Jurasz and Jurasz, 1979; and Hain *et al*., 1982, all cited in Clapham, 2000). The pod initiates an attack by rushing the prey while issuing loud calls. The herring swim upwards in an attempt to escape but at the same time another whale, the bubble blower, swims in a circle above the school and deploys a curtain of air which both traps the prey and channels them to the surface, whereupon all the whales feed upon them. Interestingly, this strategy not only involves precise spatiotemporal coordination between the herders and bubble blower, but the bubble blower, vocalizer(s), and herders all appear to specialize in their subtasks (Sharpe, 2000, personal communication).

Killer whales (*Orcinus orca*) also hunt cooperatively (Martinez and Klinghammer, 1970; Similä and Ugarte, 1993; Baird and Dill, 1995; Baird, 2000). In one attack on a Dall's porpoise reported by Baird and Dill (1995, p. 1306), ''two whales alternately engaged the porpoise in a high speed chase.'' Presumably, the two concurrent subtasks ''chase'' and ''rest'' were necessary to catch this fast-swimming prey (however, see Section VII.A). Baird and Dill (1995) also report several cases in which harbor seals (*Phoca vitulina*) hid from killer whales in underwater crevices and caves. To prevent the prey's escape while the whales surfaced for air, the whales seemingly coordinated their time below water so that at least one whale was always guarding the prey. Baird and Dill (1995) also report several cases in which female whales would attack seals while adult males prolonged their dive, possibly to prevent the prey's escape from below. Finally, Baird (2000, p. 142) cites Guinet's (1992) study in the Crozet Archipelago in which ''individuals maintained specific foraging positions relative to other individuals, both within and between years and between different bays.''

Bottlenose dolphins also exhibit division of labor when hunting. Würsig (1986) cites Tayler and Saaymen's (1972) study in which some bottlenose dolphins (*Tursiops aduncus*) herded fish to shore while others prevented escape. Würsig (1986) himself reports a case in which a group of five bottlenose dolphins coordinated their attack so that three offshore and two nearshore dolphins arrived at the prey synchronously. Finally, Bel'kovich *et al.* (1998) provide quantitative data on the frequency of what they term the ''wall method'' in which groups of dolphins drive prey towards the shore or towards one or more other individuals that are waiting. Dolphins sometimes also form alliances of two or three males to control the movement of females. When recapturing a fleeing female, ''rather than chasing directly behind the female, the males often angled off to either side, effectively cutting the distance if she changed direction.'' (Connor *et al.*, 1992, p. 987). Interestingly, fish may also employ similar cooperative strategies when they hunt—specifically yellowtails (*Serriola lalanderi*) attacking jack mackerel (*Trachurus symmetricus*) and Cortez grunts (*Lythrulon flaviguttatum*) (Schmitt and Strand, 1982 cited in Würsig, 1986, and Dugatkin, 1997).

C. Carnivores

Griffin (1984, 1992) describes a hunt by lionesses (*Panthera leo*) that he observed in Kenya that appeared to involve teamwork. Five lionesses were hunting wildebeest (*Connochaetes taurinus*) that had separated into two

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groups. Two lionesses sat in conspicuous positions atop two mounds but posed no threat to the prey while, without being seen, a third lioness slinked along a ditch so as to position herself between the two herds. A fourth lioness rushed out of the forest towards one of the herds, which charged towards the other herd and the waiting, hidden fifth lioness. As the herd jumped the ditch, this lioness caught her prey, which was then shared among the lionesses. Although not conclusive proof of teamwork, it certainly has the appearance of an intentional coordination (Griffin, 1984) and a successful strategy involving division of labor among the lionesses. Similarly, Alcock (1979, p. 320) reports that ''sometimes a lioness or two will leave the other members of a group lying in ambush. They will then circle conspicuously around a herd of game animals and drive them back towards their fellow ambushers.'' Most significant, however, is Stander's (1992) study of lioness hunts in Namibia. He was able to recognize individual lionesses through their markings, tags, and radio transmitters. He found that some individuals habitually took up the same relative position in different hunts; that is, some individuals appeared to be ''wingers,'' individuals who always tended to go around the prey and approach it from the front or side, while others act repeatedly as ''centers,'' individuals who habitually chased prey directly from behind. Teamwork in capturing young animals, in spite of their mothers' best efforts to protect them, may occur with both jackals (*Canis aureus*) and hyenas (*Crocuta crocuta*); one individual distracts the mother while another captures the youngster (S. Harris, personal communication).

Relay running, as in the aforementioned killer whales, is known in wolves (*Canis lupus*; Mech, 1970, pp. 230–231) and also in African wild dogs (*Lycaon pictus*; McFarland, 1985). Additionally, in the latter species, ''a dog at the rear sometimes will cut corners in an attempt to head off prey'' during a chase (McFarland, 1985, pp. 136–137). It is worth stressing that such a relay strategy, in which one or more individuals can somehow rest, only works if the prey's path is non-linear and there are corners to cut.

Finally, Godwin and Johns (2002) describe a novel reason for team formation in carnivores: defending captured prey from interlopers of other species. They witnessed two African wild dogs working together to protect their impala kill from a hyena; while one dog approached the hyena from the front, the other dog darted in and bit the hyena on the rump.

D. Primates

Highly cooperative and coordinated hunting in chimpanzees (*Pan troglodytes*) has been observed at Gombe National Park, Tanzania, and more frequently in the Taï National Park, Ivory Coast (Boesch, 1994a,b;

Stanford, 1999). In both cases, one or more individuals act as drivers, forcing the prey towards waiting teammates. For instance, Boesch (1994a; p. 1143) reports, ''I once saw Frodo slowly driving the colobus down the slope in a region of high forest, while Beethoven and Prof chased them by climbing up under their line of retreat, whereas Evered, looking up at this progression in the trees, ran fast on the ground to get ahead of their advance and climbed into a tree into their path. As at Taï, the oldest male was taking up the more demanding role.'' These chimpanzees appear to use facultative hunting strategies. When trees are short the hunting chimpanzees are more opportunistic, while when trees are tall ''they adopt a more planned and collaborative hunting strategy because red colobus monkeys maintain larger distances from them'' (Boesch, 1994a).

Primates may form teams for other reasons. In a much-cited example of male coalitions in olive baboons (*Papio anubis*), Packer (1977) describes how two lower-ranking males will collaborate to gain access to estrous females. The troop's dominant male usually escorts such females. One low-ranking male keeps the alpha male busy by causing a fight while the other male goes off with the female. Later, the males switch subtasks. This is clearly an instance of a team. Both subtasks, ''keeping the dominant male occupied'' and ''mating with the female,'' must be performed concurrently, with the task being ''to achieve a mating for one of the members of the team.''

IV. Robot Teams

As in the sociobiology literature, definitions of teams and teamwork in artificial intelligence and multirobot systems literature are scarce. Hexmoor and Beavers (2001) state that ''to our knowledge all multi-robot experiments use the term team loosely as multiple robots that collectively perform a task and no analysis is offered.'' Indeed, here we attempt such an analysis. Singh (1998, p. 303), however, does provide a more concrete team definition: ''multiagent systems that are viewed as having different members playing specific roles and usually cooperating to achieve some higher end.'' Thus, like that of animal societies (Sections II and III), a team consists of two or more individuals (''multiagent systems''), involves division of labor (''playing specific roles''), and has some mutual goal (''cooperating to achieve some higher end''). Hexmoor and Beavers (2001) also recognize that team members ''share a joint persistent goal'' and further add that ''the team persists so long as the achievement goal persists,'' an important issue that is developed later (Sections V.B and IX). Interestingly, Singh (1998, p. 303) recognizes that a team may contain components which themselves are teams: ''when a team is opened up with the design stance, we find not mere mechanisms, but other agents, some of which may be teams''—a conclusion at which Anderson *et al.* (2001) also arrive in their analysis.

Unfortunately, the studies by Singh (1998) and Hexmoor and Beaver (2001) are atypical and it is clear that when one surveys multirobot literature the term ''team'' is indeed used loosely, ambiguously, and inconsistently. In their review, Cao *et al.* (1997, p. 17) state that one of the major aims for the emerging field of collective robotics is to develop ''robust definitions and metrics for various forms of cooperation.'' Our aim in this section, therefore, is to provide a critique of teams and teamwork in the multirobot literature (how have roboticists really used the term?) and to analyze whether our earlier task type classification scheme is relevant to cooperative, multirobot systems. In short, we ask whether the same fundamental issues of teamwork and groupwork identified in animal societies (Sections II and III) also apply to robots.

A. Examples

Many studies in multirobot systems involve collectively moving an object, usually a box but sometimes a light or furniture, to some target point (Kube and Zhang, 1994; Parker, 1994; Rus *et al.*, 1995; Matarić *et al.*, 1995; Brown and Jennings, 1995; reviewed by Cao *et al.*, 1997). However, only some of these systems involve division of labor. Those without division of labor are thus groups rather than teams (*sensu stricto* Anderson and Franks, 2001; Section II.A). In some cases, a single individual can move the box. Hence, this is a task that could be an individual task—and *is* such a task when all but one of the robots breaks down—but the robots, when possible, tackle it as a group (Parker, 1999). In other cases, however, the box is so heavy that two or more robots must work in concert to move it (e.g., Kube *et al.*, 1993). In this situation, it is inherently a group task for those particular robots (an important distinction clarified in Section VIII). We now wish to concentrate on illustrative examples that we consider to be teams.

Gerkey and Matarić (2001) describe what they term a cooperative ''pusher-watcher'' scheme. Two robots, pushing at either end of one face of a box, must manipulate the object towards a goal. However, as the box is relatively large, they cannot see the goal. Therefore, a third robot is positioned between the goal and the box and issues orders to the other two robots in terms of their required relative velocities. (Gerkey and Matarić [2001], state that that they took inspiration from humans moving furniture.) This is clearly a team; there is a group subtask, ''move box,'' performed by the two pushers and an individual ''direct movement'' subtask performed by the watcher.

In Brown and Jennings's (1995) pusher/steerer scheme, there are just two robots, one on either side of the box. The robot nearest the goal is the only robot that knows the required path, and its sole job is to steer. The other robot's role is to push both the box and the first robot. Brown and Jennings (1995) liken this to a car, the rear wheels providing the force to move the passenger compartment, while only the front wheels steer. In some runs, the two robots switched subtasks so that they could perform a parallel parking movement that allowed them to navigate sharper turns and narrower free spaces. Under Anderson and Franks' (2001) definitions (Section II; Table I), this is clearly a team with two individual subtasks, ''push'' and ''steer.''

In an interesting twist (pun intended), rather than push an object, Donald *et al*. (1999) describe a cooperative robot system in which objects are pulled by a rope. Three robots are required. Two of the robots (*A* and *B*) are joined by a 5-m length of rope. Their role is to wrap the rope around the object so that it crosses itself once. Using the tension and friction of the rope, these two robots can then move in various ways to rotate or translate the object as desired. The tricky part is that in order for the rope to be crossed, one of the robots must ''step'' over the rope. However, when the rope is on the floor, there is the potential for it to slip under the object. Hence teamwork is required.

The whole sequence is as follows. Robot *A* remains stationary. Robot *B* keeps the rope taut and circles almost completely around the object. Robot *C*, the only robot capable of grasping the rope, moves forward and holds the rope (leading directly to *A*) against the corner of the object. Robot *A* moves forward allowing *B* to step over the now-slack rope (which is still held against the object by *C*). The rope is made taut again and robot *C* lets go. Here there are two main subtasks—an individual ''grasping'' subtask (performed by *C*) and a team subtask involving two individual subtasks: ''wrapping rope'' (performed by *B*) and ''tension manipulation'' (performed by *A*).

Box manipulation is not the only area of cooperative, multiple robot systems that seems to involve teams; robots also play football (soccer) in teams, another large area of robotics research (Kitano *et al*., 1997; Balch, 1997). As in human football, a goalkeeper primarily protects the goal, while others in the team try to move the ball forward towards, and ideally into, the opponent's goal. Here there is crucial division of labor, even if individuals may occasionally switch between subtasks (cf. our baseball example earlier, Section II.A). A final example (see also Section VII) includes exploration of a novel building with two robots, one mobile robot carrying a light and a second, stationary robot (with a camera) who interprets the building's configuration from the shadows cast (Langer *et al*., 1995).

B. Why Use Groups and Teams?

Even though there is little consistency in the use of the term ''team,'' there is a very strong consensus and recognition of the benefits of when and why groups and teams are useful, more so than in other fields. Why design a group or team of robots to complete a task rather than a single, more complex robot? We should stress that the following reasons are general and applicable to teams in all fields.

We find the following four major reasons for using groups and teams (Kube *et al*., 1993; Cao *et al*., 1997; Hexmoor and Beavers, 2001; Dudek *et al*., 2002):

1. *Lack of Ability*: A single individual may not have the capabilities to complete the task and thus requires help from another individual (e.g., *Camponotus* and *Myrmicaria* in Section II.C; see also Section VIII). An example is pushing boxes that are too heavy for an individual to move alone (Section IV.A).

2. *Efficiency*: A group or team may be able to complete the task more quickly, effectively, or efficiently than an individual; this is particularly so when the task is spatial. For instance, fire fighting may be more effective if a set of robots can space themselves around the fire (Kube *et al*., 1993). At the lowest payoff level, we may find that *N* individuals complete the task *N* times quicker than a single individual; consider a set of non-interacting robots collecting randomly-strewn trash (this may not, in fact, be a group or team at all, but several individuals working in series-parallel [*sensu* Oster and Wilson, 1978]). This may be useful if there is some time constraint for the task (e.g., to complete the task as quickly as possible or within a certain time frame) (a TIME_LIM task sensu Balch, 2002). At the next payoff level, interactions among individuals may generate superefficiency (cf. *Eciton* in Section II.D). For instance, interacting trash-collecting robots that actively avoid each other will tend to spread themselves across the area and complete the task more quickly than noninteracting robots (Balch and Arkin, 1994; Balch *et al*., 1995). At the highest payoff level, a team makes use of differences among individuals (known as heterogeneous systems in robotics), and members focus on the subtasks at which they are particularly adept.

3. *Redundancy and Fault Tolerance*: Groups and teams may be relatively fault-tolerant, especially in homogeneous systems with distributed control (Quinn *et al*., 2002). If a single, complex robot (rather than a group or team) fails, the task cannot be completed. When redundancy is built into the system, however, and this is

especially true of groups, failure of individuals may immediately be compensated for by others. This could be particularly important in difficult terrain, for example, on the surface of Mars or in a minefield where some individuals are likely to fail or are very difficult to replace, or with unreliable equipment in general. In heterogeneous systems, for example, highly specialized teams involving individual subtasks and also slave/master systems, failure of a key individual (e.g., the watcher in Gerkey and Matarić's 2001 study, above) may mean failure of the whole system.

4. *Cost*: Individuals in a group or team may be simpler, and therefore cheaper, to design and produce than a single robot that must complete the whole task itself (Castano and Will, 2002). First, simple interactions among individuals with the right set of feedbacks may result in the desired group-level behavior. In this way, the complexity of the system is self-organized and emergent, and not within the individuals themselves (Franks *et al*., 1991; Bonabeau *et al*., 1997; Camazine *et al*., 2001; Anderson, 2002). Such systems are often scalable, robust, and constantly seeking new solutions (Kube and Bonabeau, 2000; Anderson and Bartholdi, 2001; Dudek *et al*., 2002). Second, the members of a specialized team may be easier and cheaper to design per se—compare the cost and design issues in a task-specialized screwdriver versus a generalist tool such as a Swiss-army penknife, which includes a screwdriver capability (McShea and Anderson, 2003).

We conclude that we do find that the same issues of teamwork, such as number of individuals, division of labor, and concurrent action, do apply to multirobot systems. Our fundamental task types and their associated definitions can be used to classify and distinguish robot system behavior in a meaningful, logical, and consistent manner. Finally, roboticists have an especially clear understanding of the pros and cons of teamwork, lessons that other fields may use. Indeed, as Cao *et al*. (1997, p. 1) claim, ''The constructive, synthetic approach inherent in cooperative mobile robots can possibly yield insights into fundamental problems in the social sciences (organization theory, economics, cognitive psychology) and life sciences (theoretical biology, animal ethology).''

V. Human Teams

We now turn our attention to human teams. Teamwork in human organizations has received enormous attention in recent years, and many authors suggest that a team-based architecture is the key to an efficient,

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adaptive modern day company (Katzenbach and Smith, 1993; Applebaum *et al.*, 1999, and references therein). In this study, however, we focus on whether the notion of teamwork, as viewed by management theorists, matches that of biologists and roboticists.

C. Anderson and E. McMillan (2003) recently examined the parallels between insect teams and self-organizing human teams. Here, we summarize and build upon their findings.

A. What Constitutes Human Teamwork?

Table III lists some team definitions from the management literature. A number of common attributes are apparent. First, a team consists of a small number of individuals, usually defined as ''two or more.'' Second, there is a strong notion that these individuals are interdependent and must coordinate their activities—thereby implicitly suggesting group or teamwork (*sensu stricto* Anderson and Franks, 2001). Third, the members of a team work together towards a common objective or goal. Larson and LaFasto's (1989, p. 19) definition is probably the most succinct.

> A team has two or more people; it has a specific or recognizable goal to be obtained; and coordination of activity among the members is required for the attainment of the team goal or objective.

Larson and LaFasto (1989) further qualify their definition by excluding situations in which the team's accomplishment is merely additive, the sum of individual matches and performance, as in a Davis Cup Tennis Match. (A doubles tennis match, however, in which a pair of players on one half of the court must work together to cover the court and return the ball would count as teamwork [Anderson and McMillan, 2003].) Thus, for Larson and LaFasto (1989), Katzenbach and Smith (1993), and perhaps Shonk (1982, 1992) too, a team is more than the sum of its parts and requires coordinated, cooperative action—in other words, like social insect and robot teams, human teams accomplish results that individual members working alone could not.

The similarity between Anderson and Franks' (2001) definition and these management-based definitions, particularly Larson and LaFasto's, is striking to say the least. At this level of analysis, the fundamental issues of teamwork are similar in ants and humans, despite a 10^4 to 10^5 fold difference in average, individual brain volume (ants: Jaffe and Perez, 1989; humans: Milner, 1990). Of course, human teams do have other attributes that are not greatly relevant in ants and robots: the notion of mutual accountability, the notion of team identity, issues of trust, leadership and so on. However, such issues are not the major, common attributes of

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TABLE III
VARIOUS TEAM DEFINITIONS FROM THE MANAGEMENT LITERATURE
(ARRANGED CHRONOLOGICALLY)

1. ''A team is 'two or more people who must coordinate their activities to accomplish a common goal' [Plovnick *et al*., 1975]. The common goal and the required coordination make them a team. It is not enough for people to want to coordinate because it would be nice. Coordination must be required to accomplish the task in order to be a team [Shonk, 1982]'' (Shonk, 1992, p. 1).
2. ''A team has two or more people; it has a specific or recognizable goal to be attained; and coordination of activity among the members of the team is required for the attainment of the team goal or objective'' (Larson and LaFasto, 1989, p. 19).
3. ''A group of people is not a team. A team is a group of people with a high degree of interdependence geared toward the achievement of a goal or completion of a task'' (Parker, 1990, p. 16).
4. ''A team is two or more people working together to achieve common goals'' (Mackay, 1993, p. 26).
5. ''A team is a collection of individuals who exist within a larger social system such as an organization, who can be identified by themselves and others as a team, who are interdependent, and who perform tasks that affect other individuals and groups'' (Stewart *et al*., 1999, p. 3 citing Guzzo and Dickson, 1996).
6. ''A team is a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable,'' and that there is ''the need for any team to produce something of incremental performance value that is more than the sum of each member's efforts'' (Katzenbach and Smith, 1993, pp. 45, 89).

teamwork as listed in the definitions in Table III. However, even in Anderson and McMillan's (2003) more detailed analysis, which appears in Table IV, it is clear that most of their attributes are common.

B. SELF-ORGANIZING TEAMS

While most readers would probably expect some form of leadership in a human team, this is not always so. They may be self-organized (Stacey, 1996; McMillan-Parsons, 1999; McMillan, 2000; Anderson and McMillan, 2003). By this, we mean teams that are informal and temporary, form spontaneously around specific issues, and in which no member of the team has an organizational or leadership role. Consider the immediate, unplanned cooperation when friends, neighbours and family members help to excavate a trapped person after an earthquake; in a self-organized team most or all individuals make decisions and may ''lead'' spontaneously as circumstances dictate (see McMillan, 2000, and McMillan-Parsons, 1999, for detailed management examples). Essentially, self-organized teams constitute a tight social network with adaptive, emergent properties. On an organizational and decision-making basis, rather than being hierarchical

TABLE IV
COMPARISON OF LIKELY ATTRIBUTES OF HUMAN AND INSECT TEAMS

Team Attributes	Human Teams	Insect Teams
Definable membership of two or more	Yes	Yes
Team consciousness or identity	Yes	No
Common, overall purpose or goal	Yes	Yes
Members interact, communicate, and influence each other	Yes	Yes
Members have complementary skills and abilities	Yes	Yes
Activity is coordinated	Yes	Yes
Team has ability to act as one	Yes	Yes
The members consider themselves mutually accountable	Yes	No
There are performance goals	Yes	No
Team members evaluate themselves	Yes	Yes
Team evaluates itself	Yes	No
There are emergent properties	Yes	Yes

After Anderson and Mcmillan, 2003

and command-and-control driven, they are flat and decentralized. Acknowledging that these human teams are only a subset of human team diversity, we propose that self-organizing teams come closest to a truly common, fundamental team-type, equally applicable to social insects, robots, and humans.

The way that human teams form is also instructive. They form in response to an issue or an activity that motivates people to take action and create an informal and temporary team (Stacey, 1996). The team would not exist without an impetus that was considered important and worthwhile. Significantly, Anderson and Franks (2001, p. 538) arrive at the same conclusion. ‘‘Teams in social insects only form in immediate response to the stimulus of a team task.’’ For instance, an encounter with a large forage item that cannot be moved alone or the need for an urgent nest repair. Multirobot systems are only now starting to approach this stage of organizational flexibility and response; that is, that an individual robot may recognize a task that needs doing, that it requires cooperation, and that it has the ability to recruit assistance from other robots (T. Balch, personal communication). More research is needed in this area.

VI. Team Size

Team size is an interesting aspect of teamwork. Multirobot systems typically involve less than 20 individuals (T. Balch, personal communication) but those that classify as teams (*sensu stricto* Anderson and Franks,

2001) are much smaller, generally consisting of just two or three members. In management, companies may consist of hundreds of thousands of employees yet their teams also tend to be small, often with just 3 to 15 members (Peters and Waterman, 1982; Katzenbach and Smith, 1993; Anderson and McMillan, 2003). Similarly, although insect societies span more than five orders of magnitude, their teams are also small. (Teams, however, are typically expected and found only in larger insect societies; Anderson and McShea, 2001a.) Although no quantitative data exist, from the descriptive natural history (Section II) we predict the median team size is probably just two. There are examples of larger teams, for instance *Pheidole* and *Pheidologeton* intruder decapitation squads, and especially *Oecophylla* nest construction teams which may contain many tens of individuals in their pulling chains (group subtasks). However, what may be key is the number of functional components or subtasks (Table II)—just two or three in all known social insect and other animal teams. It would be very instructive to conduct a rigorous, quantitative comparison of team size in all these fields.

Why should teams be so consistently small? Some companies claim teams of up to fifty members, but these are dismissed outright by Katzenbach and Smith (1993) on the basis that they do not contain the strong personal interaction and collaboration needed in a team. Also, human face-to-face conversations typically fragment into dyads and subgroups when there are more than four participants (Dunbar, 1996). In both cases, might individuals be less able, comfortable, or efficient in dealing with such a large social network when the individual links of that network require such close attention and cooperation? Thus, it is possible that teams are generally small because team*work* necessarily requires such close coordination of activity. The more heterogeneous the team and the more subtasks there are, the harder it is to form an effective team—hence the above comment about the number of functional components. (Another possibility is that it is easier for a selfish individual to "cheat" somehow in larger teams.) One strategy that may overcome such difficulties is to use the work itself or other cues as both a collation and filter of individual performance; that is, use "cooperation without communication" (Brown and Jennings, 1995; Cao *et al.*, 1997; Dudek *et al.*, 2002). For example, in *Eciton* prey retrieval or robot box-pushing teams, a new individual attempting to join the team may have little or no knowledge of the other members, but can assess their overall performance from the speed and motion of the prey item or box. Such "filtering," though "the sensory capabilities of even the lower animals exceeds present robotic capabilities" (Parker, 1999), may allow roboticists to design much larger teams in the future.

VII. Testing for Teamwork

Given our numerous, proposed teams, how does one rigorously test whether a particular instance really is a team? In this section, we suggest how this might be achieved. First, however, using some borderline cases, we wish to illustrate some of the difficulties associated with such testing.

A. Borderline Cases

Tasks do not always fall neatly in the four different task types (Section I.A; Table I). Borderline cases exist. Given the complexities of animal behavior and the complex interrelationships between (sub)task types—for instance, that a team task may contain partitioned subtasks, and vice versa (Anderson and Franks, 2001)—perhaps this is inevitable. These borderline cases, however, can be instructive. Here, we deliberately seek out such cases to explore the conceptual boundaries of teamwork and provide some additional clarification as to what is, and is not, teamwork (at least from our perspective).

1. The boundary between task partitioning and teamwork

Parker (1990: p. 17; his team definition appears in Table III) suggests that a relay race constitutes teamwork. However, we consider this a partitioned task under our definitions (Section I.A). After each of the first three runners in a relay has passed the baton to the next runner, their job is complete; they do not need to participate any longer and yet the task can still be completed successfully. It is thus clear that these subtasks are sequential. However, let us now consider a pair of killer whales, *A* and *B*, alternately chasing prey (Baird and Dill, 1995; Section III.C). If *A* tires out the prey first, and then lets *B* take over, if *A* never participates again in the chase or capture, this is likely a partitioned task. However, if *A* later takes over to give *B* a rest—and importantly, it is crucial that while *B* is chasing, *A* must rest to regain strength—then necessary concurrency is introduced and this unit can be called a team. Thus, one must pay careful attention to the specific subtasks when assessing whether cooperative activity truly classifies as teamwork.

For a second example, consider the following: Jung *et al*. (1997) describe two robots cleaning a floor. One robot can sense and sweep fine particles into piles; the second robot can only sense the piles (not the fine particles) but is equipped with a vacuum cleaner. At first sight, one might consider that they are a cooperative team: One sweeps, one sucks, and because of the robots' individual limitations, there is a necessary division of labor. However, they are not necessarily a team. Potentially, the sweeper could

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sweep the whole floor, leave the room and never return; later, the vacuumer would arrive to complete its subtask. Here the subtasks would be sequential and, overall, it would be a partitioned task. Consider instead a situation in which the room was very windy or involved some other disturbance that quickly dispersed the piles. If the piles had to be vacuumed very soon after being swept (see Balch, 2002) then this might classify as a team, the two robots having to work more closely together. Here, the basic subtasks in the two situations are unchanged, but the constraints (that the piles must be vacuumed quickly after being made) can switch the task type from partitioned to team.

2. The boundary between groupwork and teamwork

In our example of cooperative hunting in humpback whales (Section III.B), one whale blew a bubble net while the others herded the prey and thus there is an unmistakable division of labor. However, situations are not always so clear. What are we to make of the following: ''Würsig (1983) has described how dusky dolphins herd anchovies in the open ocean, diving and swimming at them from below and from the sides while vocalizing loudly. This results in a tight ball of anchovies; and the dolphins take turns swimming into the aggregation and seizing fish while others continue the herding from outside the ball'' (Griffin, 1992, p. 61). Are the dolphins a group, each individual acting similarly and merely taking prey when it gets the chance, or would one consider this some form of division of labor? We suggest that they are not a team—removal of one individual will likely not have a great impact on the group behavior and success until, however, the density is so low that the fish may escape—but this is definitely a borderline case.

Here is another borderline example. A set of autonomous robots must map the floorplan of a building. Each robot does a random walk through the building, and at regular intervals scans 360° to spot other robots; if it has a direct sightline to another robot, then that means that there must be open floor without any intervening walls, columns, or other features between the two (Dellaert *et al*., 2002). Over (very extensive) time, the set of recorded sightlines converges on the true floor plan—this procedure is termed diffusion mapping.

One could argue that this is a group task because the algorithm relies on having multiple individuals and each individual's task is identical: ''to wander the building and sight other individuals.'' Alternatively, one could reason that there are two separate subtasks, a case of ''see and be seen,'' and although ''be seen'' is a passive subtask, nevertheless it is a crucial, different subtask and the robots are a team. We take the latter stance, although again, it is not entirely clear. Interestingly, the robot's sensors and range finders are not entirely accurate and any errors in an individual's series of sightings are additive. As such, the set of sightings—the map—may ''drift'' over time. Therefore, Dellaert *et al*. (2002) include several static individuals that do not move and who act as reference points used to correct for any drift. With these individuals, there is no ambiguity; it is a team.

B. Experimental Tests for Teamwork

How then does one test for teamwork? We start with a lesson learned from an earlier section. *Detection of superefficiency* (although an *a priori* seemingly reasonable test) is *not* sufficient. We have mentioned teams as being ''more than the sum of the parts'' (Sections II.D and IV.A; also Table III). However, as mentioned in our robot section, a set of trash-collecting robots that actively avoids other robots will tend to disperse itself across the environment better than a set of non-interacting, randomly roaming robots and so may work especially effectively. Indeed, they may be superefficient (Balch and Arkin, 1994; Balch *et al*., 1995). Hence, somewhat surprisingly, we must consider that groups are potentially superefficient as well.

Let us recapitulate Anderson and Franks' (2001) team task definition: a task that necessarily requires multiple individuals to perform different subtasks concurrently. The ideal test, therefore, would be to conduct a series of experiments to show that members of the supposed team are performing different subtasks concurrently (i.e., that *different individuals* must do *different things* at the *same time*) and that this is essential for the task to be completed successfully.

The first obvious and necessary step is careful observation of the potential team and individual activity. First, this will help identify possible subtasks and their interdependencies. Second, and more importantly, although observation can never positively prove the existence of teamwork, through the logic of falsifiability (Popper, 1959) it may conclusively *disprove* teamwork. For instance, one may observe that two concurrent subtasks are not always performed at the same time.

Next, through careful experimentation, individuals would be removed (or somehow impaired), one at a time, from a large series of replicate putative teams. This is most easily achieved in robotics—the off switch—and is reported in the literature (e.g., Parker, 1999). Such individuals should exemplify all of the possible subtasks, and each type of putative team member should be removed from a suitably large series of replicated teams. The supposed subtasks individual team members are performing should be identified before they are removed. Ideally, quantitative and qualitative predictions should be made about how the missing individuals and their associated deleted subtasks will lead to the failure of the collective task. We should stress that removal of an individual and subsequent failure of the task is not sufficient per se to demonstrate teamwork. For example, imagine a box that requires the combined strength of at least 1.5 robots to move it. Two identical robots are moving the box with ease, but removal of one of them reduces the remaining effort sufficiently that the task fails, despite the fact that the two robots are a group.

Ideally, the removed individual should be replaced or substituted by other individuals. This should enable all the necessary subtasks to be performed and should restore full team performance. In short, this method would involve the classical experimental techniques of vivisection and restoration. Thankfully, as we are dissecting the society and not individuals, it is easy, comprehensive, and painless (cf. sociotomy experiments [Lenoir, 1979a,b; Lachaud and Fresneau, 1987] or Wilson's pseudomutant technique [1980a,b]). Such experiments are likely to be most difficult with vertebrates, as individuals might become alarmed by the removal of their workmate or may recognize that a particular individual is missing.

Certain experiments to demonstrate teamwork have been conducted on army ants (Franks, 1986, 1987; Franks *et al.*, 2001) and in some of these cases the team task was so strongly associated with particular prey items that a second team with properties similar to the initial one could be shown to form around the replaced items.

Most intriguingly, we suspect that it may be possible in the near future to replace team members in certain animal societies with machines such as robots or even rather simple mechanical devices that can substitute for certain subtask performances. For instance, initial tests have begun on sugar cube-sized Alice robots with which ants directly interact (G. Theraulaz, personal communication; illustrated in Caprari *et al.*, 2000 Fig. 4; Caprari *et al.*, 2002). Less sophisticated is the possibility of adding tiny wheels to certain army ant prey items to substitute the back runner in their ''penny farthing teams.'' Such manipulations should help to clearly establish the form of the subtasks and hence the divisions of labor that may occur in animal teams.

When such experiments are not possible, the putatively distinct subtasks of different team members should be quantified and classical bottom-up modeling (e.g., Camazine *et al.*, 2001) should be performed to demonstrate that the successful performance of the collective task is the sum of the different performances and the interactions of the different members. Once again, this is most easily achieved in the field of robotics as most robotic experiments are first simulated before being tested with actual robots.

In addition, especially in cases where full ablation, restoration, and experimental protocols cannot be achieved, it may be possible to get the putative team to operate in different controlled and treatment environments. For instance, one may be able to alter the relative ease, speed, or efficiency at which different subtasks can be performed, independent of the individuals tackling them (e.g., making a box more heavy in a robot ‘‘push-a-box’’ task). In this way, changes in team performance might be proved to result from the various subtask contributions of the different team members.

C. Case Study

As an example of the above testing procedures, we highlight Quinn *et al.*’s (2002) study of three homogeneous robots whose task was to remain within sensory range of each other and move a certain distance as a group/team in an obstacle-free environment. Each box-like robot is equipped with four infrared sensors and is initially placed in a random configuration within sensory range of each other. Thus, successful task completion consists of two sequential phases: reorienting into formation and then group translation. There was no particular required formation, simply one that worked—the study’s greater objective was to *evolve* a successful group level strategy using an evolutionary algorithm. The system was first evolved in silico and then implemented with real robots.

Successful strategies evolved in which the robots moved together (Fig. 2), but were they acting as a team? They moved in a line, but had a leader/follower scenario arisen as the authors had supposed? To demonstrate that each individual made some crucial but different contribution to the overall success, Quinn *et al.* (2002)—who had adopted Anderson and Franks’ (2001) team definition—removed individual robots and studied the effect upon the remaining two.

Removal of the middle robot simply left the other two out of sensory range, while removal of the rear robot caused overall translation of the remaining pair to cease. They were not motionless, however, and entered a dynamically stable, cyclical pattern in which they oscillated (through rotation only) in anti-phase to one another. Replacement of the third robot soon restored group translation. Finally, removal of the front robot caused the middle robot to swivel around and soon thereafter enter the same cyclical pattern that resulted when the rear robot was removed. Quickly rotating the middle robot by 180° or moving the rear robot to the front caused the group to move in the opposite direction. This latter result thus demonstrates that roles are spatially determined and are not robot specific. Quinn *et al.* (2002) thus found that (1) the rear robot did not affect the

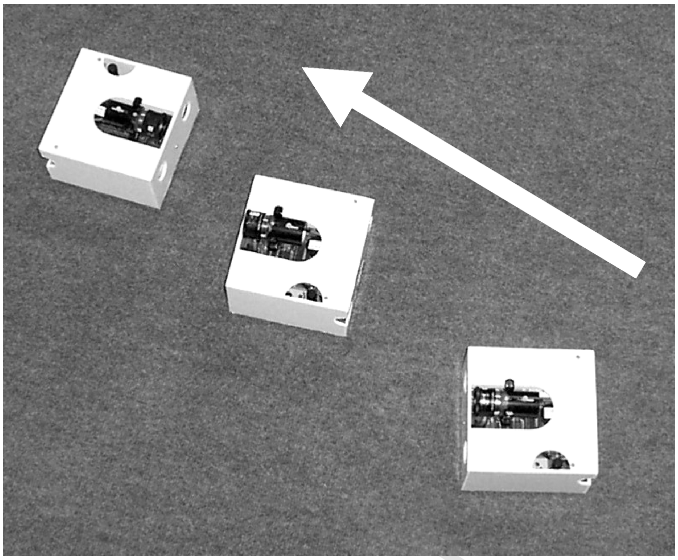

FIG. 2. A three-member robot team travels in the direction of the arrow (courtesy Matt Quinn.)

other two robots' formation ability but was crucial for translation; (2) the middle robot moves forward in response to the rear robot's presence, and hence the rear pair must persist for group translation; and (3) the front robot is crucial as well. They conclude that ''these robots are working as [a] team, concurrently performing separate but complementary roles which, in combination, result in coordinated formation movement,'' an analysis with which we agree.

VIII. Misconceptions About Teamwork

In this section, drawing on the ideas and examples presented above, we will expose a number of misconceptions about teamwork. When dealing with such diverse teams and diverse social systems as we do in this chapter, it is inevitable that certain issues are particularly relevant in some systems but less so in others. Hence, the following clarification operates on a fundamental, almost philosophical, level. Our aim is to show that certain claims and ideas about teams, resulting from the perspective of one field (e.g., robotics) do not appear to be true when considering teams from another field (e.g., social insects). That is, they are not *fundamentally* true of teams in general; thus, essentially, the following is an attempt to spell out some of the more important, generic features of teams.

Misconception #1: Groupwork is synonymous with teamwork. The most common misconception appears to be the assumption that concurrent activity among multiple individuals must be teamwork (e.g., Balch, 1997, called his trash collecting robots a team). This is not necessarily so. As we emphasize above, and as Katzenback and Smith (1993) stress in their much-cited book on management teams, it could just be groupwork—that is, necessarily involving concurrent activity, but not necessarily requiring division of labor (Section II.A). Indeed, it may simply be an example of series-parallel activity (Oster and Wilson, 1978), that is, individuals independently engaged in individual tasks, but just happening to be working simultaneously. Only when both concurrent activity of multiple individuals and a division of labor is required to complete a task successfully (for a certain set of specified individuals, see below), does activity class as teamwork.

Misconception #2: Teamwork requires interindividual differences. Teamwork does not fundamentally require interindividual differences (e.g., *contra* Hölldobler and Wilson, 1990). Our earlier example of the parcel-tying helper (Section II.A) was designed to illustrate this point; even your clone could have aided you. Despite the fact that teamwork involves a necessary division of labor, this does not imply that team members must be fundamentally different or specialized for their subtasks. However, selection pressures (natural or otherwise) in all the very diverse systems in which teamwork is employed may well favor interindividual differences and constancy in tackling those subtasks for which the individuals are particularly well-suited (Section II.A).

Misconception #3: Teamwork requires individual recognition. Teamwork does not fundamentally require individual recognition (cf. Katzenbach and Smith, 1993). Again, our parcel-tying example illustrates this point (Section II.A). You do not need to know who this helper is, or ever interact with them again, for you to work together as a team. However, and this is an important distinction, in certain situations in which interindividual differences are crucial, to successfully in complete tasks you may need to recognize the *skills* in those potential team members (e.g., as members of a certain *class* of individuals but not necessarily as individuals). For instance, a group of *Pheidole* minors may have pinned down an intruder and need to recruit a major to decapitate the victim. If recruitment is an active process (rather than a major, by chance, encountering the immobilization activity), then the ants must recruit a major because only a major can complete the task. This then would require distinguishing between majors, who could complete the task, and minors, who could not.

Misconception #4: Some tasks are inherently team tasks. As it stands, the assertion ''Some tasks are inherently team tasks'' is false (cf. Parker and Touzet, 2000). The type of task is only defined within the skills and constraints of the individuals tackling it, in addition to any external constraints (e.g., that the task must be completed within ten minutes; Balch, 2002). A tough task for some types of individuals, requiring cooperation and assistance, may be a trivial task to other, more highly skilled individuals (Balch, 2002). This is exemplified in the case of the large *Camponotus brutus ants* who could milk *Caternautellia rugosa* nymphs alone, whereas the smaller *Myrmicaria opaciventris* ants had to work cooperatively (Dejean *et al*., 2000; Section II.C). Therefore, what is needed to correct the above misconceived statement is a qualification; for instance, ''Given the skill set of the individuals, α_1, α_2,. . ., α_n, and the constraints β_1, β_2,. . ., β_n, task X is necessarily a team task.''

A second reason why the earlier assertion is wrong, at least from a philosophical rather than a practical standpoint, is that a task may be viewed as being of a different type when viewed from a different hierarchical level. This is best explained through an example. Consider an adult human unscrewing a jar of peanut butter. Our focal level is the whole organism level, the human. This jar-unscrewing task would usually be an individual task; he or she can open the jar without requiring help from other individuals. (This would not necessarily be true, for example, for weaker, young children though—another illustration of the point made in the previous paragraph.) However, shifting our focus down to the level of the hands, this is a team task, one hand holding the jar (subtask 1) while the other screws off the lid (subtask 2). This concept is not as abstract as it first sounds because it may be useful and important to view a group or team as a functional unit, a black box in the grander organizational scheme of the social entity. For instance, the head of a large company may wish or indeed *need* to view his or her organization solely from the perspective of interacting teams. From their perspective, to view it at a lower level may mean that they do not see ''the wood for the trees.'' To a personnel manager, however, perhaps only the individual level will suffice. In short, tasks may involve two sorts of hierarchy; first, that of the hierarchy of subtasks (e.g., a team within a team and so on), and second, that of different focal hierarchical levels. Only when the latter is changed, may the overall type change.

Misconception #5: Efficient teamwork requires direct communication. As teamwork involves crucial concurrent action, activity must be coordinated appropriately and effectively. This implies that teamwork requires some form of information exchange among members. However, intermember communication need not be direct. There are at least two other alternatives for the mediation of communication—through the work in progress and through the environment.

Certainly in social insects, and perhaps also in human and robotic teams, effective coordination and communication—through signals and *cues* (*sensu* Lloyd, 1983)—can be channeled through the work itself. This is known as stigmergy (Holland and Melhuish, 1999; Camazine *et al*., 2001). Consider the example earlier of *Eciton* and *Dorylus* ants forming teams to transport prey (Section II.D). To transport the prey at the standard retrieval speed, it seems that a close match is needed between the weight of the prey item and the combined weight (and therefore strengths) of the ants themselves. New individuals attempting to join a team can probably sense their contribution to the team by the change in speed of the prey item when they start to help. Likewise, individuals already transporting the item can likely sense the contribution of the new ant through the same mechanism. Thus, the speed of the prey item acts as a cue to the new individual as to whether its efforts are useful to the team (Franks, 1986). Roboticists cite a number of similar examples of "cooperation without communication," such as coordinated box pushing (Brown and Jennings, 1995; Cao *et al*., 1997; Dudek *et al*., 2002).

Consider a mountain rescue team whose members work concurrently to search for and then rescue some lost climber. The team may first break up into pairs, each of which searches a different section of the mountain. If for some reason direct communication (e.g., radio contact) is not possible among the pairs, they could still coordinate their activity through some signals left in the environment. For instance, to let others know that the search had been called off or to signal that a certain area had been checked, they could leave a colored flag or a pile of rocks in a conspicuous location. Provided that everyone knew the specific meaning of such signals, indirect communication could be effective among the team members.

Misconception #6: Teams require a leader. Teams do not necessarily require a leader, contradicting the majority of the management literature. Many teams have leaders, or at least key individuals who play a crucial coordinating role, but many teams, including all of our social insect examples, do not. There are various reasons why a team may not have a leader. Indirect communication, as described above, may be sufficient or even preferable to coordinate activity, rather than a dedicated, specialist individual who leads the other team members. For instance, if the size of the team is large or the subtasks complex, it may be very difficult for a leader to collect and process the information about the team's activities and then send out directives for the next step. Therefore, self-organized and hence leaderless teams (as considered in C. Anderson and E.

McMillan, 2003) may be more effective. In addition, no member of a team may have the cognitive abilities, experience, or other skills required to lead. Either way, it is clear that leaderless teams do exist. As in the many definitions of teams within this article, however, the key issue of teams is not leadership but appropriate and effective *coordination* of the team members' contributions, whether it occurs through leadership or not.

Misconception #7: Team members need to know the state and goals of other members. One does not necessarily need to know the state or goal of other team members (*contra* Hexmoor and Beavers, 2001; see also Stone and Veloso, 2002, p. 44). As mentioned above (Misconception #5), the behavior, and additionally, the state, of an individual may be mediated through the task. For instance, in Brown and Jennings' (1995) pusher/steerer system, the state of the steerer (its wheel orientation) is effectively channeled through the box to the pusher. Hexmoor and Beavers (2001) also claim that, ''agents with nontrivial ability and objectives who are not aware of other agents sharing their objectives cannot partner [for teamwork].'' Nontrivial is obviously subjective, but ants, as far as we know, are not aware of other ants' goals and intentions (in short, we believe that they lack a ''theory of mind,'' Premack and Woodruff, 1978), but do work as teams.

IX. Conclusions

In this chapter we have considered what it means to work as a team in several fields, namely robotics, management, and sociobiology. We have detailed many new examples of teams, especially in sociobiology, and also demonstrated a number of generic lessons (chiefly in Sections VII and VIII). Through our various illustrative examples and the remarkably similar definitions across fields, we have elucidated some fundamental issues and concepts of teamwork. These are principally captured in our generally applicable definition of a team task: a task that necessarily requires multiple individuals to perform different subtasks simultaneously. As stated earlier, our approach focuses on the structure of tasks (Ratnieks and Anderson, 1999; Anderson *et al*., 2001; Anderson and Franks, 2002). As such, the question of why individuals may work as teams, especially the matter of common goals, is not relevant to our perspective, but nevertheless is an important issue of teamwork.

Teams form to tackle a particular task; the team only exists as long as the goal exists (Plovnick *et al*., 1975; Stacey, 1996; Hexmoor and Beavers, 2001; Section V). However, more research is needed concerning the heuristics and algorithms by which teams form, operate, and disassemble.

The proximate mechanisms can be very simple. For instance, for an *Eciton* worker deciding whether it should join a team, its rule may be "join so long as you increase the retrieval speed, but do not exceed the standard retrieval speed" (cf. Franks, 1986, and Franks *et al*., 2001; Anderson and McMillan, 2003). In this manner, individuals can easily self-select themselves for team membership without overseers and leaders, and without the need for predetermined roles (*contra* Belbin, 1981, 1983; Anderson and McMillan, 2003).

In all fields, the degree of heterogeneity and the specialization of team members is an important facet of teamwork research. Significantly, how teams are assessed, rewarded, and selected can be crucial. If such selection operates at the individual level, then this tends to promote homogeneity, whereas heterogeneity is promoted if it operates at the team level (e.g., Balch, 1997, and Quinn *et al*., 2002, in robotics). Obviously, in most cases it is the new, team-level functionality absent at the individual level, that is desired and is why teams are principally used. This is most often voiced in the management literature with the following acronym: *TEAM* = *T*ogether *E*veryone *A*chieves *M*ore.

Constraints, both these placed upon the task and the individuals tackling it, play a crucial role in work organization. As stated earlier, no task is inherently a team task (Section VIII) unless it is qualified by the skills and limitations of a set of focal individuals. Even then, it is perfectly possible that the same set of individuals may tackle the task as individuals on some occasions and as a team on others (Anderson and Franks, 2001; Section VII.A). Teamwork not only allows a task to be completed successfully when a set of individuals working alone are doomed to fail (especially if the team is superefficient), but also may simply allow the task to be completed more quickly, effectively, or efficiently.

Cao *et al*. (1997) cite the need for "robust definitions and metrics for various forms of cooperation" as a major challenge for the future of cooperative mobile robotics. Anderson *et al*. (2001) have begun progress on this by developing a new metric for quantifying the structural complexity of a task on an interval scale. Once the structure of the task has been found, as in the left-hand column of Table II, one point is assigned to each "individual" subtask, two points to each "group," and three to each "partitioned" or "team" subtask; these are simply summed to give an overall complexity score for the task that can used to rank different tasks or teams (see Anderson *et al*., 2001 for more details). We suggest that our metric could easily be used in robotics, and although such a structuralist perspective is unusual in management, it could potentially be used here too (P. Saul, personal communication).

We have attempted to unite seemingly disparate fields. We believe that this has been successful both within and across each field. Direct benefits arise because both similarities and differences are illuminating. We believe that we have been able to expose generic principles within human management, robotics, and especially animal behavior by focusing on the work itself rather than the workers. This approach focuses attention on the tactics and mechanisms of social interaction and later on the strategic benefits. Thus, both levels of explanation—the how and the why—come under scrutiny and are mutually benefitial.

X. Summary

We have considered what it means to work as a team in several fields: robotics, management, and sociobiology. We have demonstrated that a single, generic definition of teamwork—a task that necessarily requires multiple individuals to perform different subtasks simultaneously—applies in vastly different social systems; in other words, we suggest that teamwork is a fundamental aspect of cooperative activity in highly social systems. We have detailed many new examples of teams, especially in non-human animals, and also demonstrated a number of generic lessons about teams, especially in our sections in which we draw attention to a number of misconceptions about teamwork (Section VIII) and in which we specify how one objectively and rigorously tests for teamwork and distinguishes it from related phenomena such as groupwork (Section VII).

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