

A Paradigm for Self-Organisation: New Inspiration from Ant Foraging Trails

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Abstract. Self-organised biological systems are robust, flexible and adaptive. They respond to changing conditions in a manner which is desirable in emerging computational systems. The problems solved by Pharaoh's ants are analogous to those challenging modern computer science; specifically dynamic or continuous optimisation problems. Pharaoh's ants utilise multiple chemical pheromones for communication (and memory) over divergent time scales. Furthermore, there is a division of labour between pathfinder scouts who persistently search for the optimal solution and generalised foragers who exploit the current best solution. This subtle balance means that multiple solutions can be maintained while an optimum is still sought, but alternative solutions are kept available. The remarkable sophistication of this self-organised ant foraging system clearly exhibits many desirable properties. The aim of our project is to take inspiration from these properties and deliver novel ant algorithms, which can apply to the problems of autonomic and autonomous systems.

1. Introduction

There is a growing recognition that many seemingly unrelated networks share common characteristics, but it is a very different matter to apply this insight in making computer or telecommunications networks more robust. For example, the new appreciation of the true architecture of the Internet provides us with the means to generate similar networks to test new protocols for information exchange [18]. However, understanding the basic architecture of a network represents only one part of any effort to protect it against failure or attack. Consequently there is a growing

belief that complex networks can be managed in a more sophisticated way emulating analogous systems in nature. Study of natural networks holds the promise of new insight into how distributed systems are best managed and designed. Research in this area is timely as it is becoming clear that many distributed systems have reached a critical mass, thus demanding that decentralised control must be achieved.

Recent inspiration from nature has yielded genetic and evolutionary algorithms (GA and EA), simulated annealing and Ant colony optimisation (ACO). The class of heuristic search algorithms known as ant algorithms, in particular, have proven to be very effective in solving combinatorial optimisation problems. However, thus far ant algorithms have only applied one aspect of how complex insect societies solve problems in a concerted parallel fashion: the use of a single pheromone in discovering a shortest path solution. Here we describe new insights that have emerged from our research into how a self-organised communications network is managed in nature – the pheromone-mediated foraging trails of Pharaoh's ants (*Monomorium pharaonis*).

2. Networks – Natural and Artificial

Networks increasingly dominate our lives and not just through the familiar examples of telecommunications networks or the Internet. Recent research in many domains has found that networks pervade all areas of biological, social and man-made systems. Much of the current interest in networks can be attributed to the broad movement towards complex systems research. This in turn sprang from the great challenge to scientific disciplines of reassembling physical elements into entire ensembles to produce accurate and complete descriptions of complex systems [3, 15]. However, the current inability of science to describe systems composed of non-identical elements, with diverse and non-local interactions, is limiting the advancement of our understanding [15]. An increasingly popular aid to describing complex systems is that of representing them as abstract networks, whose vertices are the elements of the system and where the edges represent interactions between them [18]. These networks are discernible at every organisational level in natural and artificial systems, extending from genetic regulation to social interaction in biology as well as the familiar examples of computer and financial networks. However, networks are inherently difficult to understand for several main reasons *i.e.* structural complexity, network evolution, connection diversity, dynamical complexity, node diversity and the interactions between each of these factors [18]. To make progress in describing these networks it is usual to simplify by making assumptions that remove some problems. For example, network architecture is often treated as static so as to avoid issues of structural complexity and concentrate on system dynamics. The logical next step would be to combine dynamical and structural complexity, but the mathematical tools to achieve this have yet to be delivered. As a consequence, characterisation of network topology in many branches of science has been the major focus, which has led to encouraging progress, especially when combined with the powerful tool of computer simulation.

A general insight to have emerged from network research is that the development of large networks is governed by robust self-organising principles, which go beyond

the particulars of individual systems [3]. For example, biological transport and communication systems have evolved to minimise energy expenditure in the distribution of resources or information *e.g.* root systems, cardiovascular system, lungs and nervous system. Almost universal scaling laws characterise such systems, particularly those governing the transport of nutrients in plants and animals [23, 24]. These laws have their origins in common geometric and hydrodynamic principles that conserve energy in fluid transport. The same power laws have been identified in other networks describing dynamic resource movement, particularly the Internet. The network architecture applicable to these types of network is commonly known as the 'small-world network': regular networks with nearest neighbour connections, in which some edges are randomly rewired to become long-range connections, turning these nodes into hubs. Such hubs are connected to a very high number of other nodes.

With our new appreciation of network architecture the next step in understanding systems is the study of system dynamics. How a system behaves over time in a changing environment can best be understood by identifying essential mechanisms underlying specific behaviours [15]. Solving dynamic problems is routine in nature and understanding how this is achieved at a fundamental level (the agent rules) could provide invaluable insights applicable to telecommunications and computing networks. For example, we know that many ant species use pheromone trails to orchestrate colony behaviour in foraging for resources, and have a grasp of the fundamentals. The process is simply presented as ants forming a single trail to a food source by repeated trail deposition on their return to the nest. By a feedback mechanism the strengthening trail recruits more ants and food is rapidly transported back to the nest. The volatility of the pheromone (negative feedback) means that the trail is easily abandoned when the food is exhausted because reinforcement no longer occurs. Refinements of this general mechanism have been employed in ant algorithms for combinatorial optimisation.

The basis for ant algorithms was observation of pheromone-mediated foraging, which focussed upon very few ant species – *Lasius niger*, *Lasius fuliginosus*, army ants (*Eciton* spp.) and the Argentine ant (*Linepithema humilis*) [4]. These ants vary greatly in their reliance upon pheromone trails for orientation. However, the vast majority of models for pheromone trail formation have focussed upon *L. niger* [4], a species that mainly lays trails only on its return from food. *L. niger* is not reliant on pheromone trails because this ant species primarily uses vision for orientation and only uses trails to 'train' nestmates in the route to food. If the trail is removed ants so trained can still find their way between the nest and food, using their visual memory.

Many ants living in large colonies are highly reliant upon pheromones for orientation with some being totally blind, for example, the driver ants (*Dorylus* spp.). The process of foraging in such colonies is much more orchestrated with no place for egocentric behaviour. It is suggested that memorising of routes is only useful when inhabiting a stable environment with relatively fixed food resources (for example, aphids) [2]. But if the environment is more dynamic and competitive, food must be rapidly acquired when available. Furthermore, many ants living in large colonies regularly shift their location by emigration to move into areas with superior resources. This is spectacularly demonstrated by army ants, which move through their environ-

ment, carrying their colony with them, consuming all they encounter [20]. However, a closer look at their movements actually shows they have a more long-term sustainable strategy whereby they rotate swarm raids through their territory giving areas sufficient time to recover before raiding them once more [20]. Orientation in army ants, and it appears the rotation system, are mediated by pheromones. It is also well-documented that army ants produce a characteristic network of trails during their swarm raids, which focuses the search of foraging ants within a constrained area.

We study the Pharaoh's ant (*Monomorium pharaonis*) a small species (c.2mm) which forms complex networks of pheromone trails ramifying throughout its foraging environment. These trails are formed even before food is found [9] and effectively subdivide the environment during search. Pharaoh's ants are almost wholly reliant on these trails for orientation [10] and as a consequence the way they function is more sophisticated than that generally conceived. We have shown that the trail pheromones used by Pharaoh's ants act as different memory types over very divergent time scales. In addition we found a division of labour in foraging exploration and exploitation, which is mediated by behaviourally specialised castes (ant types) [11, 7]. Here we describe the process of trail formation and the strategic use of the network in the long-term, before discussing the potential applications of this insight. To aid our understanding of how dynamic problem solutions are achieved from a fundamental level we include specifications for two individual agent types in the form of X-machines. X-machines are an easily accessible, modular approach to agent-based modelling of biological systems and their elements, which are readily checked for inconsistencies and incorrect assumptions [14].

3. Trail Pheromones of Pharaoh's Ants

Ant pheromone trails utilise diverse chemicals from many glandular sources and a single species may employ multiple trail chemicals with different roles [1]. For example, in the fire ant *Solenopsis invicta* putative roles have been assigned to six different pheromones employed in trail making [22, 21]. A thorough understanding of communication via trail pheromones demands quantification of the physical parameters of chemical components employed and the behavioural responses they elicit. As a starting point we can say that trail functionality will depend upon trail persistence and equally trail longevity must adaptively meet the foraging requirements of a species. In ants, trail longevity varies from minutes in *Aphaenogaster albisetosus* [8] to several weeks in some army ants [20]. Clearly short-lived trails can modulate recruitment to ephemeral food sources, whereas long-lived trails are better suited to persistent, or recurrent, food sources. However a combination of both types might allow a colony to maintain a memory of sites that were previously rewarding and to focus on specific sites of immediate value. This two-level memory is what we have demonstrated in Pharaoh's ants.

The Pharaoh's ant is a model system for investigating trail-based foraging and at least seven trail chemicals elicit trail following in this species [11]. Faranal, which

was extracted from the Dufour's gland at trace levels, is the most active pheromone in eliciting trail following, but six alkaloids (monomorines) abundant in the poison gland also elicit powerful trail following responses [12]. Both the poison gland and Dufour's gland empty into the sting apparatus which means the two classes of trail pheromone can be separately, or jointly, secreted onto trails. This diversity of chemicals eliciting trail following in Pharaoh's ants suggests that their trails should have complex characteristics. Indeed, behavioural studies have already confirmed this by indicating the retrieval of information over long and short time frames.

The short-lived nature of trails was demonstrated with the finding that trails made on newspaper could decay within 8 minutes [13]. Our recent study [11] clearly showed that foraging trails of Pharaoh's ants can persist for longer periods, up to two days, when established by ants passing a point on a trail more than 4000 times. This volume of ant traffic is not large and can readily be achieved in less than two hours by a typical nest of 2500 workers. We further found that trail longevity was a linear function of the logarithm of the ant traffic that formed it, showing that trail decay corresponds to a standard exponential model. Our data enabled us to predict that for a trail to be re-established after one day of non-use would require 1900 ant passages, or approximately 1000 foraging trips. But for trails to persist for four days or longer would require more traffic than can realistically be made by a species whose nests contain less than 3000 workers. Our data suggests that trail longevity saturates, and it may be that reduced trail reinforcement occurs once a threshold pheromone concentration is reached, possibly because a high concentration of pheromone inhibits further deposition. Pharaoh's ants, as mentioned earlier, make frequent emigrations and do not feed from fixed resources. However, some food finds may persist in the environment for longer than a day and it is useful to mark such finds for subsequent exploitation. But to mark them for longer periods could lead to unrewarding visits on future occasions. In a dynamic environment greater flexibility in switching between resources must be vital for success. Persistence for two days would prevent unnecessary visits after that period, but should the resource persist for longer the trail would be reinforced anyway.

We demonstrated that the trail laid by Pharaoh's ant contains a pheromone component with long-term persistence, serving a different role to the short-lived pheromone component. A likely candidate for the short-lived pheromone would appear to be faranal, which is present only in trace amounts and is readily degraded in the environment. The alkaloid trail pheromones (monomorines) originating in the poison gland make good long-lived trail components because they are very stable, low volatility compounds [12]. The most active of these in eliciting a trail-following response are monomorphine III and monomorphine I. Further work has shown that these two monomorines are both persistent components of the trail but that they serve subtly different roles [12]. It is now clear that utilising multiple chemical components with greatly differing persistence enables ant colonies to retain a memory of trails and feeding sites within a large area, whilst still permitting great flexibility in short term recruitment to those feeding sites which are currently rewarding.

4. Behavioural Specialisation in Trail Re-establishment

Our research has also discovered a simple but fundamental behavioural specialisation exhibited by individual foraging workers, which mediates their ability to detect a long-lived trail. Successful detection occurred only in ants walking slowly with antennae held low and making frequent contact with the substrate. These findings are in contrast to ants following well-defined trails, which generally walk at a continuous pace with antennae raised, making infrequent antennal contacts with the substrate [11]. Because only ants with their antennae touching the substrate can detect it, the active space for the long-lived pheromone must be very small, as a consequence of low volatility. The ability to follow this pheromone cloud is restricted by the ant's threshold for detection, such that a vapour tunnel of pheromone exists (the active space) [26].

We discovered a division of labour in the exploration of long-lived trails. Only 27.5% of foragers were successful at detecting long-lived trails, whilst the remainder completely failed to detect them. We also found that isolation, food deprivation and feeding had significant effects on trail finding ability. However, irrespective of treatment 21% of workers never detected the trail whilst 17% always succeeded. Other workers were capable of making a flexible transition to trail finding when deprived of food, although they always performed poorly in the trail-finding test. We suggested that the workers, which could always locate and follow the long-lived trails (17% of foragers), were specialised "pathfinder scouts". Pathfinder scouts followed existing long-lived trails to locate persistent food sources. The behaviour exhibited by pathfinding foragers may actually be permanent as their frequency in the forager population (c.20%) was repeatedly confirmed. This implies the existence of behavioural castes determined by different response thresholds for long-lived trail detection behaviour. Pharaoh's ants ensure an efficient commitment of workers to reinvestigating previously rewarding trails by allocating only a small proportion of the foraging workforce to scouting each morning. During periods of food deprivation further foragers could make the transition to this role ensuring that all the trails available are searched, thereby increasing the probability of locating food. The inferior long-lived trail following skill of those making the transition is also adaptive, as this could also lead to fresh food discoveries in areas off the trails because trail departures are more frequent in non-pathfinders.

The role of Pharaoh's ant pathfinders is thus to leave the nest early in the morning and explore the trunk trails used on previous days in order to locate any persistent food sources. Pathfinders leave the nest "along definite routes which they follow more slowly and hesitantly than ants on a true scent trail" [19]. When pathfinders successfully located food they returned to the nest and rapidly recruited further foragers. After this process of trail re-establishment was completed all ants interacting with the previously long-lived trail were capable of following it to the end, but only if pathfinders had located food. After finding food pathfinders 'open' the trail for all other ants, apparently by depositing a pheromone detectable to all (presumably the short-lived pheromone). In a subsequent study we found that pathfinders are also frequently U-turning ants, which deposit pheromone continuously so as to ensure a trail is maintained [7].

5. Trail Networks of Pharaoh's Ants

The use of long-lived pheromone trails as an environmental memory of previously rewarding feeding sites has received little attention. Our work has identified novel aspects of a system that is generally regarded as simple but which is in fact highly sophisticated. This suggests that there must be important adaptive benefits from utilising multiple pheromones with widely differing decay rates. Clearly it is adaptive to lay persistent trails to rich feeding sites enabling their reuse the next day because Pharaoh's ant colonies are diurnal [19]. It is probably also of adaptive significance that Pharaoh's ant trails do not persist beyond a few days, because if a trail is unrewarding for two days it may be better to discontinue exploring that trail. In addition, long-lived trails are only accessible to ants displaying the appropriate behaviour, which our data shows is the specialised caste of pathfinder foragers. This is important, as it would be costly to allocate a large proportion of the worker population to slowly exploring long-lived trails, openly exposed to predators. In marked contrast, volatile trail pheromones are easier to follow rapidly and facilitate rapid recruitment to food. They also allow rapid abandonment of a trail by negative feedback when the food is depleted or a superior find is made. Understanding how all these novel aspects of pheromone-mediated foraging fit together into a coherent system is our next challenge. Individual ants obey a set of rules that is determined by their individual state, and at the population level this results in the emergence of a robust network of trails that efficiently exploits the environment. The use of a physical, flexible network is a key element in the great success of Pharaoh's ants as a pest species worldwide. Such an efficient decentralised communication and transport network should be able to teach us many lessons in network management.

The Pharaoh's ant colony typically produces 2–4 trunk trails radiating from different nest entrances, the location of which remains fixed over long periods. A complex network of trails emanates from these trunks ('hubs') after initial formation and further trails, leading to new food finds, are subsequently connected to trunk trails. We reiterate that trail networks are formed *ab initio* immediately that Pharaoh's ants encounter new territory by a process called the 'land rush' [26]. The majority of a colony's population are recruited to explore the unmarked territory and within one hour an area greater than $1m^2$ will be ramified with an elaborate network of trails. After the trail network emerges, the majority of the ants return to the nest and traffic will mainly focus on trail sections leading to food. This network will persist for two days after initial formation, even if kept free of ants, and so must contain long-lived trail pheromone. Ants following the trail to food exhibit volatile trail-following behaviour which demonstrates that both trail pheromones are present. When trails are reused, on subsequent days, pathfinder ants explore the trail network to locate food. If successful they return to the nest depositing another pheromone, which is accessible to all. These ants are probably laying the short-lived pheromone, which is very active at low concentrations. How the pathfinder manages to select the trail section that previously led to food, the day after the trail network was formed, is an interesting question. Chemical analysis of the pheromone profile of individual workers shows that there is wide variation in the relative abundance of some monomorphines. This

separates the ants into two chemically distinct groups who are obliged to lay differing amounts of pheromone on trails: once again pathfinders and non-pathfinders [12]. Pathfinder ants deposit a greater amount of monomorphine I relative to monomorphine III (M3:M1 \sim 1.0) compared to non-pathfinders (M3:M1 \sim 30), which means pathfinders can differentially mark long-lived trails for their own future exploration. This mechanism ensures that the trail network is maintained (updated with pheromone) from day to day, but distinguishes the best trails for future investigation [12].

The adaptive significance of this strategy is of great interest because it shows a development from a two-level to a three-level environmental memory. We speculate that further information could be subtly transmitted through the variable ratio of chemicals on a trail, as a consequence of individual forager's modulating their pheromone deposition to transmit particular information. Trails may also convey different information over time due to variation in decay rates and the meaning of pheromones may also differ contextually. Our research is revealing the rich chemical language used by the Pharaoh's ant, which facilitates an adaptive exploration of the trail network and an efficient allocation of the workforce.

6. Models of Pharaoh's Ant Foragers and Pathfinders

Descriptions of our current understanding of Pharaoh's ant foraging are summarised as X-machine (agent) models of generalised foragers and pathfinder scouts, in Figs. 1, 2. An X-machine can be considered as a generalised Finite State Machine (FSM), but differs significantly in that memory is attached to the machine, whilst state transitions are labelled with functions that can operate on inputs and memory values, rather than the simple input/output of a FSM [11]. The FSM is incapable of modelling non-trivial data structures, so for agents with complicated behaviour that utilises memory the number of states explodes combinatorially. In contrast X-machines are much more expressive, capable of modelling both the data and the control of a system. X-machines enable us to model agents whose actions are determined by values stored in its memory, as well as their reactivity. This better captures the characteristics of biological systems than other methodologies such as FSM, Petri Nets or Statecharts [27, 16, 6].

In our models (Figs. 1 and 2) transitions are labelled with functions, the majority of which test sensory parameters against internal threshold values which control behavioural state transitions. For the sake of clarity we give verbal descriptions of functions and omit both parameter details and exact functions. A fuller exposition of these models, alongside simulations testing the behavioural constraints on agent behaviour, is in preparation. Here we focus on the methodologies employed for parameterisation of the model and description of the agent using an X-machine formalism. We describe a generalised Pharaoh's ant forager agent and a pathfinder. Agents inhabit a two-dimensional grid composed of discrete cells which can contain agents, food and pheromones. The two pheromones, faranal and monomorphine are the sole means of communication and also provide a means of orienting back to the nest location after feeding.

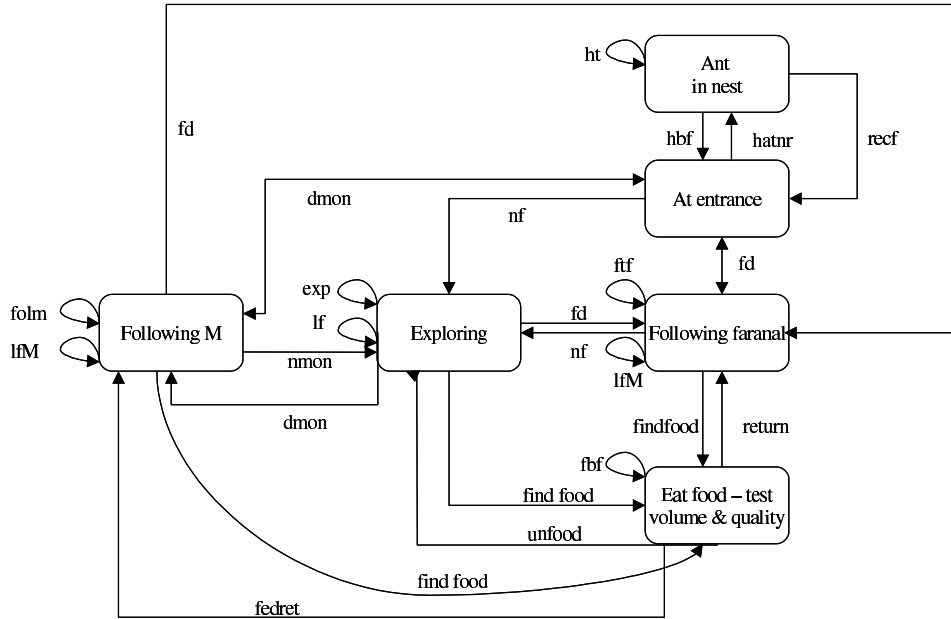


Fig. 1. Behavioural X-machine description of generalised Pharaoh's ant forager.

ht = hunger threshold test; *hbfb* = hunger threshold exceeded so locate nest entrance; *hatnr* = ant at entrance but below threshold so return to nest; *fd* = trail pheromone (*faranal*, *F*) detected; *nf* = no *F* detected; *ftf* = follow *F* trail; *lfM* = deposit *F* in the environment; *exp* = exploratory behaviour rules; *findfood* = locate food; *fbf* = feeding; *unfood* = food unsuitable so resume exploring; *lfM* = when fed deposit both *F* and monomarine (*M*); *dmon* = detect *M*; *folm* = follow *M* trail; *fedret* = when fed and *F* is not detected then follow *M*; *return* = when fed and *F* is detected then follow *F*; *recf* = recruit more agents to foraging; *Memory* = {*ant_position*, *hunger_level*, *memory_of_food_quality*}; *q₀* = (*in_nest*, *random*, 0).

Agents are initialised in the nest (Fig. 1) with a random hunger level taken from a normal distribution and with no memory of the quality of food finds. The location is a memory component only for the benefit of simulations and agents make no reference to this when making state transitions. From the initial state, in the nest, agents are tested for their hunger level which decays over time as food is metabolised. Immediately the hunger level exceeds the hunger threshold (*ht*) the agent moves to the nest entrance (*hbfb*). An additional function (*hatnr*) ensures returning fed agents that have consumed all their food on a long journey, will remain at the nest entrance. Agents can also be recruited to forage (*recf*) by other agents even if they are not hungry. From the nest entrance state, agents either detect (*fd*) a pheromone trail (*faranal*, *F*) which they follow (*ftf*) in the *Following Faranal* state or they fail to detect faranal (*nf*) and instead enter the *Exploring* state. In both of these states the goal is to find food (*findfood*) but in the two states there is a slight difference in behaviour, where faranal followers deposit monomarine (*lfM*) in the environment

as well as faranal (*lf*). Where a faranal trail is lost or not present (*nf*) agents will enter the *Exploring* state. Agents return to the nest either following faranal (*return*) when present or monomarine (*fedret*). When following monomarine both faranal and monomarine is deposited (*lfM*). The pathfinder agent (Fig. 2) differs from a generalised forager in that it recruits other ants (*recf*) but is not recruited. Pathfinder threshold values tested by functions also differ from generalised foragers, and the exact differences are being resolved by simulation.

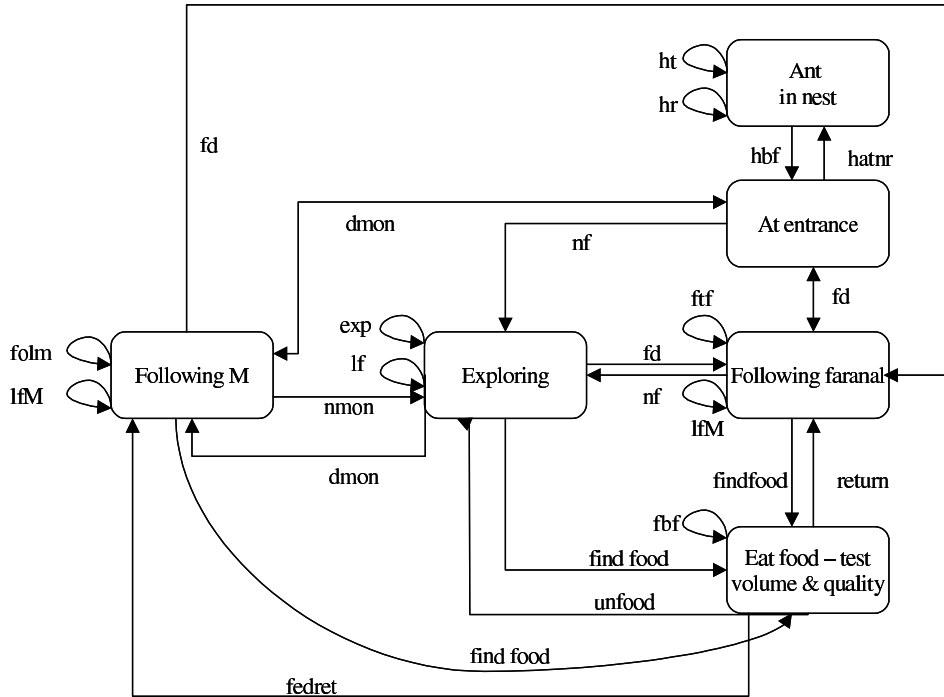


Fig. 2. Behavioural X-machine description of Pharaoh's ant pathfinder scout.

Differences from the specification of a general forager are the absence of function *recf* and the inclusion of *hr*. This is because pathfinder ants recruit to food sources whereas general foragers are recruited to them.

In further elaborations of the model the threshold values are not fixed such that their variation is dependent upon other internal memory values, particularly the hunger level. As stated earlier, general foragers can also switch to the pathfinding role when sufficiently deprived of food. To reach this state the hunger level must fall below a lower threshold that triggers the behaviour of monomarine (long-lived trail) detection. In contrast a pathfinder ant has a higher threshold for this behaviour such that it begins to follow long-lived trails immediately it becomes hungry. Several context-dependent behavioural thresholds will thus be controlled by individual hunger level, which we simply model as the amount of food ingested by the ant.

7. Inspiration and Potential Applications

Applications utilising ant algorithms have generally been based on a single characteristic of real ant colony behaviour: the use of a single pheromone in reinforcing good and potentially optimal solutions to the problem at hand [5]. Of the few exceptions to this pattern some employ multiple ant agent classes: each class is associated with a particular function of a globally distributed problem and each has access to a pheromone set enabling communication either with identical or different agent types [25]. However, trail-reinforcement is always achieved through a single pheromone. Our research on Pharaoh's ants not only confirms the utilisation of multiple pheromones in trail-based foraging, but also demonstrates great variation in time frame of the half-life of these pheromones. Furthermore, we have shown behavioural and chemical specialisation in the re-establishment of old trails by a distinct caste of pathfinder ants. The use of one pheromone limits ant algorithms from fully exploiting the strength and complexity of pheromone-mediated communication. To overcome this apparent lack of 'memory', researchers adopt unnatural and artificial structures: such as ant memory to stop them returning to a node already visited; and supplementary heuristics to encourage ants to explore potentially fruitful trails. Our study of Pharaoh's ants indicates that natural ant systems employ a much more complex and rich communication system than previously envisaged. We suggest that a fuller exploration of the computational capacity of the Pharaoh's ant search strategy can only be beneficial for a new generation of ant algorithms. However, we acknowledge that the problems being solved by the long-term search strategy of Pharaoh's ant colonies is not immediately transferable to classic computational problems. Indeed, the problem classes we intend to address with new ant-inspired strategies are those that have emerged recently with massive computational power, ever-increasing data sets and open-ended pervasive networks. The robust, flexible nature of Pharaoh's ant search makes it highly applicable to these dynamic problems.

Ant algorithms have been applied to routing problems in telecommunication networks [17], where the cost of using links and node availability varies both temporally and spatially. AntNet is the best known example and after extensively testing it has been shown to out-perform all other routing algorithms for packet-switched networks (local area networks or Internet), being highly adaptive and robust. In recent years ant algorithms have been applied to routing of mobile *ad hoc* networks where they perform well and provide robust performance [5]. This latter problem can be categorized as a dynamic optimization problem, where the search space changes over time thereby changing the available solutions. This demands that the search algorithm can respond to change and modulate its search strategy to solve the 'new' problem. Similar classes of problems are dynamic TSP and dynamic vehicle routing, where the distance between cities can change as well as the city number. Sometimes a problem has multiple objectives which require ranking according to their importance. The goal is to find a set of solutions that are optimal in a 'Pareto' sense. This problem is again analogous to that encountered by Pharaoh's ants where multiple food sources are usually simultaneously available, but foraging effort must be allocated in an efficient, adaptive manner.

The best definition of the problem faced by Pharaoh's ants, and many modern dynamic computational problems, is 'continuous optimization'. Clearly survival in a dynamic environment is a continuous problem where the optimal solution changes all the time. The best solution arrived at by the ants is to allocate a subset of the population to the task of continually striving for the optimum whilst the majority exploit the current best solution. This sounds simple but as we have seen the natural means of achieving this goal requires sophisticated communication and a flexible community of agents with access to different skills (behavioural rules). Taking inspiration from Pharaoh's ants we shall deliver some new approaches to tackling dynamic computational problems.

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