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Computing for construal: an exploratory study of desert ant navigation

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Abstract

The study of ant navigation is a rich source of empirical data and speculative theories that has been well-documented in the scientific literature. We describe and illustrate how an approach to computer-based modelling ("Empirical Modelling") can be used to devise construals to support the exploratory experimental activities that inform an understanding of desert ant navigation.

Keywords: computational science; exploratory experiment; Empirical Modelling; construal; ant navigation

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1. Introduction

A previous paper by Beynon and Russ [1] distinguishes two kinds of experimental activity: *post-theory* and *exploratory*. To date, the application of computational science has been primarily directed at post-theory experiment, which enjoys computer support well-aligned to the classical theory of computation. In [1], Beynon and Russ argue that exploratory experiment demands a broader conception of computing and propose *Empirical Modelling (EM)* [2] as a conceptual framework better oriented to providing appropriate computational support.

In this paper, we give a practical illustration of how EM can support exploratory experiment in connection with documented scientific studies in ant navigation [3,4]. Our objective is to show how EM can be helpful in devising a construal that is consistent with the empirical evidence and with speculative scientific theory. We shall first use the theme of ant navigation to review the notions of post-theory and exploratory experiment that are introduced in [1].

1.1. Post-theory and exploratory experiment

By a *theory* of ant navigation we mean a putative mechanism that explains how an ant behaves with reference to what we construe the ant as able to perceive and act in response to. Of course, this explanation of behaviour cannot

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reasonably be expected to predict the actual behaviour of a specific ant in precise detail. It should however be able to account in broad terms for the typical patterns of behaviour that can be observed from studying a real ant. Post-theory experiment concerns the study of ant behaviours that are predicated on an established theory. Such experiments can exploit the power of the computer as a computational device that simulates the repeated application of a set of stimulus-response rules.

A theory of ant navigation rests upon experimental evidence derived in a speculative and exploratory fashion. Such evidence testifies to what senses may be employed – whether an ant navigates by using scent or vision, for instance. It may also serve to corroborate a specific hypothesis about what an ant responds to - such as whether it can distinguish objects, and is sensitive to their size and colour. Other relevant ingredients that require exploration include the mechanisms that are deemed to be involved (such as recognising and remembering landmarks) and the range of environmental conditions and situations in which a navigation strategy can succeed.

We use the term ‘exploratory experiment’ to refer to activities of a preliminary and provisional sense-making nature that precede the articulation of a theory. Whereas post-theory experiment is associated with a stable objective context of observation in which parameters can be changed and the outcomes observed, exploratory experiment is concerned with identifying appropriate contexts for reliable observation, distinguishing between essential and accidental features of interaction, deciding what is deemed to be an outcome and what is deemed to have significant influence over this outcome. The scope and complexity of the exploratory investigations required in studying ant navigation reflects the richness of the sensory and navigational mechanisms involved. Such studies can benefit computer science in many ways. The naturally evolved navigational mechanisms and behaviours of ants are likely to differ greatly from those that a computer scientist might contrive, and a deeper understanding of their nature may provide useful insight into intelligent agents.

1.1. Sensory and navigational capabilities of ants – a brief overview

Ants possess a wide range of sensory capabilities, though acuity and the manner in which they are relied upon or combined differs greatly between species. Some key capabilities are as follows:

Scent: Most ant species are very sensitive to scent, and particularly scent markers left by other ants of the same species and colony. The behaviours related to the use of scent in ants are well-documented and understood. Marking paths to food with scent trails is common, as is using scent to alarm or direct nest-mates.

Touch: Ants are covered in tiny hairs, which give them the ability to feel. This is particularly useful when they are navigating the inside of their nest but can also play a significant role in navigating an outside environment. Touch is also used by many species for communicating with nest-mates.

Vision: An insect’s vision is significantly different from that of humans or other animals. They possess compound multifaceted eyes, made up of thousands of tiny *ommatidia* – primitive individual eyes with their own lens and several long visual cells. Instead of sensing Red, Green and Blue light like human eyes, an ant’s eyes are sensitive to Green, Blue and Ultraviolet light. Ants have eyes on the sides of their heads, so have a wide field of view. In most species vision is more sensitive towards the front of the ant where the two eyesight fields overlap and vision cells are most concentrated. Visual aptitude varies between species; desert ant species for example have excellent vision and make extensive use of it, while other species have severely limited vision.

Ants are also known to possess some very specific capabilities that are directly adapted for navigation and direction-finding. These include complex visual-memory navigation techniques, as well as inbuilt abilities that utilise directional cues imperceptible to humans, such as polarised light, magnetic fields and path integration:

Polarization Compass: It is well known that many insects orient themselves using the sun or moon. However, it is not strictly the sun that such insects use, but the presence of polarized light in the sky. Such insects have ommatidia that are sensitive to polarized UV light (which penetrates clouds better than the humanly visible wavelengths). These ommatidia are orientated at a variety of different angles, such that by analysing the input, the ant brain can determine the direction and intensity of the polarized light in the sky. The benefit of this complex polarization hardware to the insect is to provide a kind of compass with which to orient itself.

Magnetic Compass: Some ants can also sense their orientation relative to the earth’s magnetic field. However, this seems to be a less important ability, used only in the absence of visual guidance from the polarization compass.

Path Integration: Ants have a well-documented ability to keep track of their distance and direction from the nest when they are out foraging. Even after travelling some distance from their nest in varied directions, experiments have shown them to be able to return directly to their nest, judging direction and distance very accurately. This ability (which is not unique to ants) is called *path integration,* as when the ability was first suggested it was named after the integration technique used by human marine navigators to perform a similar function.

Experiments have since shown however that there are consistent errors in the calculations made by ants, and that they actually appear to use an approximation method that calculates the new distance and direction from the nest at every step. They are thought to estimate distance travelled at each step using sensory information from the muscles in their legs (proprioceptive senses). An algorithm that ants may use for calculating the distance and direction from the nest has been proposed by Müller and Wehner [5].

Visual-Memory Techniques (Using Landmarks and Snapshots): Navigating by use of memory and landmarks is one of the most interesting areas of ant behaviour. Ants are capable of recognising and remembering landmarks, and using them to find their way back to food sources or other sites of interest. There are, however, a variety of ways that different species of ants use and interpret this ability. Many species are thought to take 'snapshots' of their surroundings at specific intervals, which they subsequently use to retrace their steps to important objects. Different species are known to follow 'walls' and other long objects, to aim at landmark 'beacons' and to navigate using vectors. A combined example is described in the navigation scenario in section 2.2.

As explained in Collett and Collett [3], Collett, Graham and Durier [4] and Wehner [6], ants do not typically rely on one sensory capability in navigation; they combine these capabilities into an overall navigation behaviour system. By way of illustration, the combined navigation scenario discussed in section 2.2 focuses on path integration and visual techniques but excludes the scent, magnetic compass and sun compass abilities. This would be very typical of species such as desert ants (genus *cataglyphis*) that are known to use visual navigation extensively.

1.2. Support for exploratory experiment through computer-based construal

From the above discussion, the complexity of the task faced by an experimenter seeking to develop a theory of ant navigation is clear. An ant can potentially exploit many different senses in navigating, may adopt a navigational strategy that combines different capabilities, and may deploy different strategies according to its current situation. What is more, any putative explanation for an ant's navigational behaviour must make credible assumptions about the kind of processing that can be carried out in its simple brain. For instance (cf. section 2.3 below), experimental results suggest that ants can record landmarks by taking visual snapshots, and registering the elevation angle to the top of each landmark in their snapshot. When they later compare a snapshot with the current view, they are thus able to judge distance, and assess whether they are closer or further from objects than when the snapshot was taken.

Making computer models in conjunction with gathering empirical data and formulating speculative theories can be helpful in addressing the experimenter's task. Ideally, computer models constructed for this purpose should be fluid and readily revised as more data is gathered and new provisional interpretations are conceived. As is well-recognised, traditional software development principles are ill-suited to this purpose – modifying the functional requirements of a program typically means significant revision of a program, especially where the implementation has been optimised to achieve specific functional goals. The "Empirical Modelling" principles and tools advocated for this modelling role operate within a radically different semantic framework. The product of EM activity is an interactive artefact whose interpretation is unlike that of a program. Crucially, the interpretation of interaction with an EM artefact is not formally specified (as is the functional specification of a program). In contrast, the interpretation is open-ended and reflects connections made in the modeller's immediate experience that in general have to be learned and rely upon acquired observational and manipulative skills.

In his historical studies of Faraday's early work on electromagnetism [7,8], the philosopher of science David Gooding introduced the term 'construal' to refer to interactive artefacts that play a role in representation and communication similar to that of computer models in exploratory experiment.

The principles that guide the construction of computer models that serve as construals are quite different in character from those that inform classical computer programming. Empirical Modelling [2] favours an approach to building construals that involves embodying within computer artefacts the patterns of interaction observed in phenomena. The objective in this embodiment is to endow the construal with interactive characteristics that correspond closely to those exhibited by all the state-changing agents deemed to be associated with a phenomenon, as identified through exploratory experiment. In this context, the correspondence to which the experimenter aspires is primarily experiential rather than formal in character. What atomic changes of state can be observed and/or effected in the phenomenon, as identified through experiment, have direct counterparts in interactions with the computer-based construal.

1.3. The rudiments of Empirical Modelling

Three basic concepts underpin EM principles: *observables*, *dependencies* and *agents*. (For more details of these concepts, see [2].) The agents relevant to a construal include all the entities deemed to be capable of producing state-change. The primary agent is the model-builder. Conceptually, the model-builder's view of their construal is expressed as a network of dependencies linking observables. Observables in the computer-based construal are associated with scalar values, such as numbers or strings, geometric entities such as points, lines and shapes, and display components such as panels, boxes and labels. The current values of these observables reflect the state of the phenomenon as (or as if) it is currently being experienced by the modeller. Dependencies express the way in which the modeller expects a change to one observable to affect another in an atomic indivisible fashion. By using the EM tools, it is possible to specify families of observables and formulate definitions to frame the way in which the current value of each observable is dependent on the values of others (cf. the way in which the value of a spreadsheet cell can be defined in terms of the values of other cells).

The current values of observables in a construal, as displayed on the computer screen or recorded in the computer memory, together with a family of definitions of observables that express the latent dependencies between changes to these observables, are the counterparts of "the sketches of images, objects and actions" to which Gooding alludes in [8]. The full appreciation of the construal requires knowledge of meaningful ways in which the construal can be exercised by invoking suitable manual, semi-automated or fully automated changes of state, for which counterparts of the "procedural explanations and instructions" to which Gooding alludes in [8] are required.

In EM, a complex phenomenon is construed as a multi-agent interaction. The same principles that are used to frame the current state of the construal as it is experienced by the model-builder can be applied to modelling the environments within which all other agents are deemed to act. In this way, a human perspective on state and action, as mediated by a family of definitions, can be projected onto other agents. The most significant distinction between the construal and a program is that the behaviours in which the construal can participate are open-ended in respect of their extent and their interpretation. As in the processes that led Faraday from construals of electromagnetic phenomena to the invention of the electric motor (cf. [7]), there is scope for interactions with construals to expose system-like and theory-like patterns of behaviour. In this respect, there is a key role for the identification of protocols for agent interaction and of invariant relations between observables.

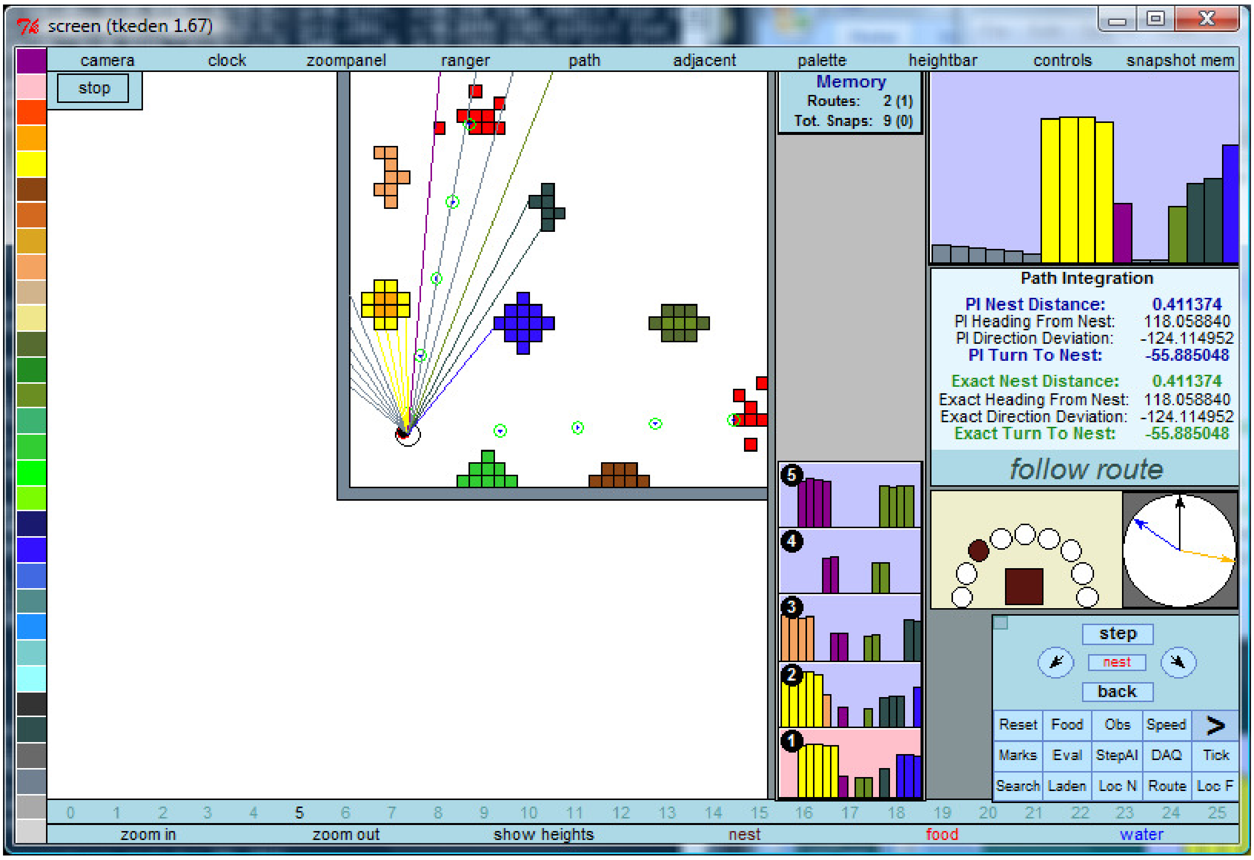
2. A construal for desert ant navigation

The principles and concepts of EM will be illustrated with reference to the development of a construal for ant navigation [9,10]. This construal was developed by the principal author, Daniel Keer, in his final year undergraduate project in 2005. In this paper we shall focus on how Keer's construal illustrates the theme of EM support for exploratory experiment. For fuller details of its construction, the interested reader should consult [9].

2.1. Keer's ant navigation model

A screenshot from Keer's ant navigation model is shown in Figure 1. It depicts the use of the model to demonstrate how an ant might make use of visual snapshots in returning to a previously discovered source of food. Developing this construal of ant navigation had three aspects:

1. Informally identifying the kinds of behaviour that were to be addressed, and the sort of observables, dependencies and agents that would need to be taken into account.
2. Constructing an interactive environment in which the relevant observables, dependencies and agents were realised and actions and interpretations on the part of agents could be rehearsed.
3. Interacting with the environment in an exploratory fashion to find coherent patterns of behaviour that conform to experimental findings.



Routes: 2 (1)
Tot. Snaps: 9 (0)

Path Integration

PI Nest Distance:	0.411374
PI Heading From Nest:	118.058840
PI Direction Deviation:	-124.114952
PI Turn To Nest:	-55.885048
Exact Nest Distance:	0.411374
Exact Heading From Nest:	118.058840
Exact Direction Deviation:	-124.114952
Exact Turn To Nest:	-55.885048

Figure 1: A screenshot from Keer's ant navigation model

Aspect 1 was addressed using a 'PEAS' specification (cf. Russell and Norvig [11], p38) – a method of analysis that defines an agent problem from the point of view of the Performance Measures, Environment, Actuators and Sensors for that agent. In this case, the appropriate agent problem was to simulate the navigational performance of a desert ant, as documented in a number of scientific papers on the subject [3,4,5,6].

Performance Objectives: The agent must locate food sources, and navigate between the nest and the source on repeat visits as quickly and as effectively as possible. As a model of a real ant, it must perform in a realistic manner (even with the same inherent flaws), and make decisions in ways that ants are understood to use.

Environment: A suitable experimentation environment will consist of a walled enclosure from which the ant cannot escape. The environment will contain objects of different colours and sizes, and which we will assume the ant cannot climb over. There will be a nest located in the environment, which the ant can recognise as 'home'. There may also be food deposits present, which the ant will be able to detect. The enclosure will be divided into a grid and objects, food and water will all occupy discrete squares on this grid.

Actuators: The ant is capable of turning by rotating around its current position. It can also step forward a predetermined step length. Though it is imagined to pick up and deposit food, these actions will have no effect on the environment.

Sensors: The ant agent possesses the following sensory abilities, a subset of those in section 1.2:

- The ant can detect the contents (e.g. food or nest) of its current location, as well as the contents of the squares directly adjacent in the forward arc (from -90^o to 90^o).
- The ant has a path integration sense telling it the distance and direction to the nest. This is regarded as an 'internal' navigation sense, and is calculated based on the algorithm in Müller and Wehner [5].
- The ant can perceive coloured objects/landmarks in the surrounding environment. To simulate an ant's long-range visual sense in the model, the ant agent is able to view the elevation and colour of any objects in front of it in its forward field of view (from -45^o to 45^o). In the model the horizontal visual resolution is limited to 17 fixed equally spaced headings within this field of vision, resolving to the 17 coloured bars visible in Figure 1.
- The ant can detect the position of the sun in the sky (which gradually shifts), relative to its current position.

Aspect 2 of the model-building made use of the principal EM tool ("the EDEN interpreter") to construct the interactive environment depicted in Figure 1. In this environment, there are counterparts of the significant observables required to explore the agent problem framed above. Because of the nature of modelling in EDEN, it is appropriate to conceptualise the current state of the environment as a family of definitions, expressing a network of dependencies that link the significant observables. These definitions were originally introduced to the model through an input window that is not currently displayed. In principle, they are still open to further extension and revision in this way. As the model-building activity matures, specific kinds of interaction are distinguished as particularly topical; the environment and interface depicted in Figure 1 has been customised for experimentation motivated by the PEAS specification.

In EM, the primary focus for the modeller is on developing the interactive environment in such a way that the many different varieties of relevant agency can be exercised within it. In studying ant navigation, the modeller shapes the environment whilst interacting in several agent roles: that of a developer with expert knowledge of the modelling tools, that of a scientist performing exploratory experiments, and that of the ant itself. A distinctive characteristic of EM is that agent interactions of all these different kinds can be carried out in precisely the same way – by redefining the values of observables in the model in an appropriate manner. It is even possible in general for two or more roles to be played concurrently. This is appropriate when, for instance, the modeller-as-scientist wishes to explore the impact of moving landmarks whilst the ant is in the process of navigating, the modeller-as-developer wishes to enhance the interface for the scientist whilst an experiment is in process, or the modeller-as-ant wishes to probe the robustness of a navigational procedure by perturbing the motion of the ant.

The roles that observables and dependencies for the various agents play in shaping the environment are illustrated in Figure 1. Observables relevant to the ant include the colour and height of landmarks in its field of vision (cf. the ant's current view of the environment as displayed in the top-right hand panel of Figure 1), as well as the current role ("follow route") it is playing and the snapshots taken on the route it is currently retracing. These observables stand in a subtle relationship to the location of the ant and the disposition of the landmarks as recorded by the modeller - a relationship that is dynamically maintained by the dependencies in the model. In this way, the ant's view of the environment is updated whenever it turns or takes a step, or when a new object is introduced into its visual field.

There is a semantically important discrepancy between the actual location of the nest and the ant's estimated position of the nest as determined by 'path integration'. The model includes observables to represent the ant's estimated position, as computed by the algorithm proposed by Müller and Wehner [5]; any discrepancy between the actual and estimated position of the nest is registered in the panel on the right-hand side of Figure 1.

Other observables in the model are significant in relation to the developer's role. By zooming in on the environment (using the button at the bottom-left of the screen display in Figure 1), it becomes possible to see the actual height of obstacles at each square. Knowledge of this kind is helpful when checking that the profile of obstacles in the ant's current view is being displayed correctly, for instance.

In EM, the interactive environment is the arena within which the behaviour of agents is realised. Creating this environment is conceptually prior to the specification of behaviours, and its refinement continues as behaviours emerge and are elaborated. The button currently labelled "stop" near the top-left of Figure 1 is used to switch on or off the animation of the ant's rule-based movement within the environment. The panel at the bottom-right of the display in Figure 1 can be used by the modeller to play the role of the ant manually (e.g. turning clockwise and anticlockwise, stepping forward or back), as well as to reset key parameters and set up specific scenarios.

The environment depicted in Figure 1 is the product of an extended development from an initial basic prototype environment devised by K-C Tan in an MSc project. The fact that Tan’s environment was originally conceived with a study of ant navigation based on scent in mind highlights the open-ended exploratory nature of this development. In its subsequent development, Keer’s model itself underwent many transformations, and in its current form reflects an emerging focus on particular experimental interactions relating to certain kinds of observed navigational behaviour. This – the third aspect of the model-building activity – is the theme of the following subsections.

2.2. Construing a combined ant navigation scenario

The modelling activity that is illustrated in Figure 1 relates to the following scenario, which describes how ants combine their path integration sense with their visual landmark recognition capabilities to navigate between nest and food. It would be fairly typical of a desert ant (*cataglyphis*):

- From the nest, an ant may set out foraging to try and locate food. When a foraging ant discovers a new food source it will collect some food, and will then face the task of returning to the nest. The ant is able to determine direction and distance back to the nest from the path integration ‘sense’, and will set off along that vector.
- At set distance intervals on the route back to the nest, the ant will painstakingly stop and turn through 180^o to look back at the way it has come from (i.e. towards the food source). It is strongly believed [3,4] that the ant is taking a ‘snapshot’ memory of the current location, recording the respective locations of landmarks on its retina. The ant will perform this task several times before it reaches the nest, thus recording an ordered set of snapshots for the route it has just travelled. Any obstacles encountered may also be navigated around.
- When the ant reaches the nest, it may ‘deposit’ the food, before ultimately seeking to return to the food source to collect more. On setting out from the nest, the ant will make use of the most recent ‘snapshot’ in memory, and will orient itself towards the visual direction that most closely resembles the snapshot. The ant will then set off in this direction until the image it sees on its retina completely matches the snapshot it has memorised. By performing this procedure for each snapshot it has stored in memory, the ant is able to retrace its steps to the food source with great accuracy – even if obstacles in the original path make the route non-straight-line.
- If the food source has not been moved, the ant will be able to return to it many times with very good precision. If for any reason it does not find the food source where expected, or finds its remembered route disrupted, it might briefly search the surrounding area before giving up and beginning a random forage for food.

In order to understand the combined behaviour of a cognitive 'ant' agent in the above scenario, the behaviour can be modelled as a set of behavioural 'modes'. Each of these modes will have certain conditions (linked to the agent's sensory abilities) under which the current behaviour will switch to another mode. Figure 2 shows the modes that were identified in the ant navigation construal, and the conditions on which the behaviour mode would change.

For example, the *At Nest* mode is the natural starting mode where the ant would, on preparing to set out, determine whether it has a route in its snapshot memory. If so, it would attempt to align itself visually with the start of the route, before moving to the *Follow Route* mode to follow a previous route back to a food source. Alternatively, in the absence of a remembered route that it can match, the behaviour might move to *Search* mode, where the ant will forage semi-randomly looking for new food sources, and avoiding obstacles.

Depending on whether the ant finds a food source, or has visited it before, it may enter *Return (Simple)* mode, the ant makes use of its path integration sense to travel directly home to the estimated position of its nest, navigating around obstacles in its path. In *Return (Take Snapshots)* mode, the ant returns in a similar way but additionally takes snapshots at set intervals on the way back. After reaching the estimated nest location (according to its path integration sense which is not entirely accurate), the ant may enter *Locate Nest* mode to search for its actual nest.

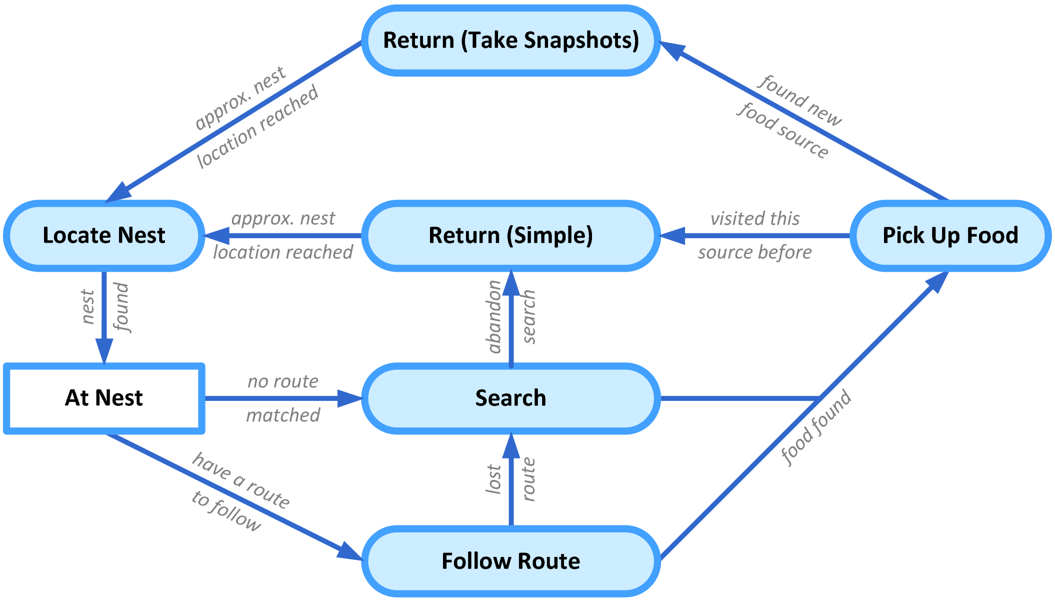


Figure 2: Behaviour mode transition diagram for the AI

Each of these behaviour modes represents a specific part of the cognitive agent's AI, of which the *Follow Route* mode is the most complex and important. This mode allows the ant to return accurately to a previously discovered source of food, by visually matching 'snapshots' stored in memory against the current viewpoint. A major aim of the project was to develop an insight into this real-world cognitive behaviour, through the process of modelling.

2.3. Snapshot following

Treating each of the AI modes mentioned above as an individual AI problem, Empirical Modelling principles were extensively applied to the process of understanding, modelling and developing the AI for each mode. Though there was limited scope to observe real ants, the documented scientific studies (which are summarised in section 1.2) contain a wealth of detailed experiments and observation of real ants. These were used to build up a complete picture of how the ant agent should behave in each mode – even including how it might handle unexpected cases (such as an obstacle, or the ant itself being unexpectedly moved).

Applying the Empirical Modelling process to the AI development, the functionality for each mode was built up in layers, and through a process of experimentation with the model - at all times referring to the picture of how the ant should be behaving. To begin with, AI algorithms and procedures were implemented with the aim of being 'as simple as possible' to produce the desired behaviours. The ant agent was then run and tested in different environments, changing various parameters or aspects of the environment, and the results closely observed to see how it matched expectations. Through this process of experimentation, observation and adjustment, the AI functionality can be incrementally refined at each stage to more closely approach the desired behaviour.

This aspect of the modelling can be illustrated with specific reference to the previously mentioned *Follow Route* mode of behaviour, whereby an ant returns to a previously visited food source by following snapshots in memory. In this mode, the ant would be expected (as per scientific studies) to follow a snapshot trail in memory by moving in the correct direction until the snapshot of current interest is perfectly aligned with visible landmarks, before moving on to the next snapshot. Real ants are capable of following these routes even around obstacles, on a dogleg path.

In realising such a mode of behaviour in the model, the key problem is to find a realistically simple reasoning mechanism that can be used to compare a route of snapshots in memory with what the ant currently sees. This mechanism must determine the correct direction in which to move to take the ant closer to the original location where the snapshot was taken. It must also estimate distance to this location, so that it knows when it has reached it.

An example of this problem is shown in Figure 1, where 'what the ant can currently see' is displayed in the top right hand panel, and the 'snapshot of current interest' (labelled 1) is highlighted on a pink background. Note that, in line with EM principles, the model has been built to show all of the ant's perceptive inputs in a visual representation, in order to facilitate easy experimentation and understanding of the agent's cognitive processes by a human user.

Initial experimentation with the model yielded several ideas about how cognitive mechanisms might be employed in the snapshot following behaviour. For example, we can consider that the ant would at each step compare the current view with the snapshot it is targeting, and compare any significant landmarks in each to see how it needs to move to line up the two views. When comparing the ant's current view with the current snapshot in Figure 1, it is apparent to a human eye that there is a large yellow landmark in both views, and that the ant would need to turn approximately four bar-widths to the right to align this landmark. The height and width of this landmark in the two snapshots also indicates that it is further away in the current view than it was when the target snapshot was made.

The next stage in the process was to convert these ideas into an actual quantitative direction-finding mechanism in the modelled agent – and one simple enough that a real ant might plausibly use a similar method. The approach explored in the model was to first resolve the 'raw visual data' (the coloured bars in the snapshot) into a set of distinct coloured objects. Classifying these objects primarily by colour makes it possible to compare the images of one or more objects in the target snapshot view with that in the current view. One simple quantitative measure that can be obtained from this is the relative height and width ratios, computed by the following simple formulae:

$$object\_height\_ratio = (height\_in\_current\_view / snapshot\_height)$$
$$object\_width\_ratio = (width\_in\_current\_view / snapshot\_width)$$

Checking these ratios for each object provides a simple measure by which to assess whether the current position of the ant is likely to be further away from (ratio < 1) or closer to (ratio > 1) the point where the snapshot was taken.

As far as movement is concerned, it is only necessary to determine the direction in which to move at each step. For each matched object, an indication of the turn needed to align the current view with the target snapshot can be simply derived from the points in the visual field at which the object starts and ends, as measured in bar-widths. A suitable formula to compute the required turn amount (in bar-widths of 11.25^{o}) is:

$$object\_turn\_factor = \tfrac{1}{2}\,(start\_point\_snapshot - start\_point\_view + end\_point\_snapshot - end\_point\_view)$$

If we apply this formula to the leftmost yellow object visible in the example in Figure 1, the estimated required turn is calculated as $\tfrac{1}{2}(3 - 7 + 7 - 10) = -3.5$, i.e. a turn to the right of 3.5 bar-widths (or 39.375^{o}). By making this turn, the ant would line up the images of the yellow object in the current view with the target snapshot perfectly.

The navigation strategy that is employed in the construal employs the average values of these metrics, computed over all discriminated objects, in order to determine movement. Assuming the snapshot contains sufficient reference points, the strategy uses the height/width ratios to determine whether the current position is still further away from the objects than the point at which the snapshot was taken. If so, it will perform any necessary turn (equivalent to the average of the turn factors) to adjust its orientation, and then take a step in that direction. If the height/width ratios approach 1, indicating that it has reached the snapshot point, it can start following the next snapshot in the route.

After implementing a basic form of this algorithm within the AI, the resulting behaviour was refined through a process of interaction with the model - experimenting with different situations and reasoning rules, and exploring their effectiveness. Particularly useful insight was gained by attempting to 'confuse' the agent by moving obstacles, the ant, or the nest, and exploring how the cognitive reasoning mechanism performed in the face of unexpected situations. Some of these same experiments are also documented in the biological studies, which gave an excellent basis for comparison; some interesting similarities were noted.

3. Conclusion

A typical activity in EM is making a model of the environment in which many kinds of relvant agents can act. Systematic behaviours and theories about behaviour then typically emerge from the modeller's interaction with this environment. The ant navigation model illustrates this kind application of EM with reference to several kinds of agents and roles, including those of a developer, a scientist and an ant. The model-builder develops cognitive perspectives on this agency through the close integration of different agent perspectives that EM affords.

The highly visual interface built into the model played an important role here. The main cognitive senses and inputs (sight, memory, path integration) are all represented visually in the display, greatly aiding human modellers to develop an insight into the reasoning problems involved, and to explore solutions (a core idea of EM). The eventual resulting agent was capable of navigating effectively around its (albeit simplified) environment, displaying a reasonable facsimile of a real ant's navigational behaviour, and using all the key senses in a realistic way.

Making EM construals promotes a fluidity and flexibility in sense-making activity that contributes to the emergence of theory out of exploratory experiment. It also represents an application of the computer in a role complementary to that in which it has been most commonly used in science to date. The ant navigation construal points to potential yet to be exploited for developing construals in conjunction with conducting live experiments.

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