CHAPTER NINE

THREE-DIMENSIONAL ANT NEST EXCAVATION USING STIGMERGIC RULES

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1 - Introduction

1.1 - Stigmergy in Nature

The world of social insects provides us with a variety of complex structures. Colonies of ants or termites, for instance, construct nests that, on a relative scale, are comparable in size to human cities. Importantly, they are the product of many thousands or millions of very simple individuals, none of whom are responsible for the overall planning or coordination. While the intricacies of how such massive designs originate remain as yet unknown, it is clear that there is no reliance on a centralised controller or explicit blueprint. Instead, stigmergy, a form of indirect communication, means that the behaviour of agents is determined by the state of the local environment, which is, in turn, the product of previous behaviour (Grasse 1959). This mechanism gives the overall appearance that workers are being guided by their work rather than directing it.

Stigmergy binds task-state information to local features of a task site, and enables communication by modifying those features. The process of constructing or excavating a nest is an example of quantitative stigmergy (Théraulaz and Bonabeau 1999), and is exemplified in Grasse’s (1959) studies on the construction of pillars by termites, where workers use soil pellets impregnated with pheromone to create these formations. By stigmergic communication, the colony is able to record its activity in the physical environment and use this to organise collective behaviour. This environmental memory may take the form of pheromone or temperature gradients, air flow, material structures, or the spatial distribution of colony elements, and provides the foundation for the insects’ indirect interactions.

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Although stigmergy helps to explain the flow of information among workers, it is important to understand that it is not a complete theory of building activity, but is instead one element in an overall set of mechanisms (Camazine et al. 2001). Its inability to explain certain behaviours will be addressed in later sections.

1.2 - Ant Nests

The construction of ant nest architecture necessitates large amounts of time and effort, which implies a significant fitness advantage. It provides shelter, microclimate choice, and defendability (Sudd and Franks 1987), and likely serves as a mechanism for integrating the colony members into an efficient functioning whole. Further, Tschinkel (2004) hypothesises that nest architectures organise colony functions to make them more efficient in converting labour and resources into larvae.

Only very recently has research begun to provide a quantitative account of ant constructions of nests in soil underground, using dental plaster casts and other materials to render the interior space in three dimensions. Such studies have identified two basic architectural units, descending shafts/galleries and horizontal chambers (e.g. Wang et al. 1995; Tschinkel 2004), common to many though not all types of ants (e.g. Sudd 1970). Although the specific dimensions of these units vary greatly between the nests of different species, as well as within single nests as they age, a common pattern found with a number of species is their top-heavy nature. That is to say, chamber volume is greatest in the upper reaches of the nest, decreasing with depth, while vertical spacing between chambers follows the opposite pattern. Figure 9-1 illustrates these features.

Ants are able to create these characteristics because they have cues to their own vertical location within the nest (Tschinkel 2004) and dig more when at lesser depths. Given the variability of temperature and soil moisture, it seems likely that carbon dioxide gradients (resulting from microbial and physical processes within soil) are the cues employed (Hangartner 1969, Kleineidam and Tautz 1996, although see Mikheyev and Tschinkel 2004 for possible counter-evidence).

Figure 9-1 Casts of *Pogonomyrmex badius* nests of increasing size: (A) a very small nest with a single vertical chamber series and shaft; (B) a medium-small nest with the beginning of a second vertical series and shaft; (C) a large-nest with 4 vertical series and shafts. The middle cast is incomplete, the lowest chambers having failed to fill with metal. Its maximum depth was probably intermediate between the large and small casts. (Image from Tschinkel 2004.)

The use of pheromones as one of the primary methods by which ants communicate with one another has been well established. For example, by laying down a chemical trail, they are able to affect their environment and in turn the movement of other ants, thereby using stigmergy to forage for food (Hölldobler and Wilson 1990). Also, queens produce a pheromone which influences workers to raise or execute other queens (Fletcher and Blum 1983). More relevantly, the presence of chemical communication among diggers has been evidenced during the rescue of entombed workers (Blum and Warter 1966). Although the precise mechanism by which digging could be amplified or attenuated has yet to be identified in ants, it is known that termites incorporate pheromones into building material before depositing it, encouraging others to deposit material at the same site (Wilson 1971). In this way, pheromones enable social insects to carry out a variety of group-level tasks.

There are likely numerous other stigmergic rules that ants use to excavate their complex nests. For instance, research has identified an
‘inertia’ that causes ants to excavate chambers in the same direction as the tunnels leading up to them (Mikheyev and Tschinkel 2004). This results in a correlation between tunnel angle and chamber angle, evident in the plaster casts of the nests. Such simple rules can therefore lead to the various features one finds in nest structures.

1.3 - Previous Models of Artificial Stigmergy

A number of studies have explored the simulation of stigmergy under artificial conditions. However, most of the work addressing ants involved clustering/sorting (e.g. Deneubourg et al. 1991) or foraging (e.g. Panait and Luke 2004), and not construction. There has been little previous research into simulating artificial ant nest excavation, although for simulations involving pheromone influences on termite pillar formation see Deneubourg (1977) and Courtois and Heymans (1991), and for a fairly primitive simulation concerning a virtual swarm of simplified termites see Mason (2002). Buhl, Deneubourg, Grimal, and Thirault (2005) investigated the digging activity of real-world termite colonies and attempted to model their findings mathematically using a two-dimensional lattice, although they focused on the relationship between colony size and nest volume and not the morphological characteristics of nest architectures.

Most of the above models were only suitable for capturing the initial symmetry-breaking phase of the construction process, and also did not explicitly represent the third spatial dimension. They were therefore unable to directly represent hollow structures or any climbing that these structures might demand. Crucially, they also failed to model various constraints on individual movement and pheromone diffusion that are imposed by the physicality of building material, and so neglected factors that may be important sources of stigmergic effects. These criticisms were addressed by Ladley and Bullock (2005), whose three-dimensional, agent-based model included the effects of these “logistic” constraints. They replicated the constructions of previous termite papers and demonstrated how the physicality of partially-built structures can help to establish and maintain these architectural features.

One obvious omission from Ladley and Bullock’s work and that before it is that none have attempted to model the construction of an entire nest from the ground down, instead often favouring one or two particular structures in isolation. In addition, Ladley and Bullock fail to include physical interference between termites and, more importantly for an all-encompassing model, they excluded any ‘picking up’ behaviour. In reality, the ongoing construction of a nest naturally involves both continual removal and depositing of material.

Research by Paulin (2004) partially attended to the nest as a whole by exploring the active homeostasis of epigeous termite mounds with changing environmental conditions. This, however, only considered the mound and not the full nest structure, only simulated eight agents in an unrealistically small colony world of 16×16×16 units, started with structures already extant, and further did not incorporate structural integrity and physical constraints (allowing, for example, floating blocks) or the effects of pheromones on the virtual termites’ movement (unlike in real life: Bruinsma 1979).

The next sections will present results from simulations which address these issues, providing the first attempt at modelling how the complete ant nest excavation process might occur.

2 - Method

For the sake of brevity, a detailed description of the computer model and the parameters used will not be included in this chapter. Further information, along with justification for the choices that were made, can be found at:

http://www.kramer.me.uk/robin/cognition.htm

The main features of the model, to summarise, were:

- a closed, three-dimensional, cubic lattice world (125×125×125 units) covered by a carbon dioxide gradient;
- the use of three pheromone behaviours: deposition, diffusion and decay;
- the use of two pheromones, the first leading to the excavation of shafts and the second chambers;
- a fixed number of identical ants (4000), able to sense pheromone and carbon dioxide gradients at their location;
- realistic ant movement influenced by physical constraints as well as pheromone and carbon dioxide levels;
probabilistic ant behaviours for both the deposition and picking up of blocks;

- a directional inertia incorporated into the probabilities involved in chamber excavation.

Naturally there are limits on the depiction of three-dimensional, colour structures using the two-dimensional, greyscale images in this chapter. Accordingly, a number of colour videos of rotating nests can be viewed at the web address above.

3 - Results

3.1 - The Model

Simulations were run with different combinations of parameter values, and those impressionistically judged to produce the most realistic nest structures were chosen. A typical run with these parameters reached a depth of eighty-three units below ground, and a height of nine units above ground. The deepest chamber was excavated at a depth of sixty-eight units. Figure 9-2 and Figure 9-3 exemplify the nests that were excavated.

Figure 9-2 An illustration of the nest excavation after 225 time steps, viewed from side-on. As in all the illustrations in this chapter, grey represents blocks that have been excavated below ground, while black represents blocks that have been deposited above ground.

Figure 9-3 The same nest excavation as that in Fig. 8-2, viewed in three dimensions.

The figures demonstrate how the model is successful in producing nests with distinct shaft and chamber units. Chambers branch off from shafts, and secondary shafts do not tend to form at the end of chambers, in line with real-world nests. In addition, the ants sometimes produce shafts that also branched, a feature often observed in nature (Tschinkel 2004).

Real ant nests display characteristics such as more chambers appearing nearer the surface, resulting in a decrease in chamber volume with increased depth (see Section 1.2). In order to account for this feature, biologists have hypothesised mechanisms based around how the ants might be cued to their depth using the carbon dioxide gradient in the soil, which could then affect their tendency to excavate chambers. Indeed, by incorporating this idea into the model, significant differences in chamber volume between deeper and shallower sections of the nest were found.

However, this real-world characteristic could also be due to simpler mechanisms. Given the probabilistic nature of the ants' behaviours, it is plausible that they excavate chambers nearer the surface merely because they are present in this region of the nest more often. Every ant will make numerous trips to the surface to deposit material they have removed, and so must repeatedly move through this area when looking for material to pick up. Because more excavation takes place nearer the surface, these areas are larger and can hold more ants, while deeper regions are unable to contain as many. The ants cannot walk through each other and so congestion lower down in the nest will tend to prevent as much activity from happening there. This means that any deposited pheromones are more likely to decay away before they can have an effect on the ants, who find it more difficult to reach such inaccessible regions. These interacting
mechanisms can be seen as stigmergic, in that the structure of the environment and the actions of the other colony members have a resultant effect on the likelihood of behaviours and hence the shape of the nest produced.

In order to determine whether chamber volume would decrease with increasing depth without the addition of a CO₂ effect on chamber excavation, ten more runs were carried out, but with parameters altered so that only one nest would be excavated on each run. This meant that the ants would only be attending to one site at a time, and so their activities would not be divided. If there were different numbers of nests on each run, then values could not be compared fairly.

Each run was allowed to continue for 150 time steps from the point when the nest was first started. Such an artificial termination condition was necessary because the nest would never reach completion (see Section 3.4) but very little activity would take place after such a long time. The resulting nest was analysed and the data were collected over all runs. Statistical calculations showed a significant decrease in chamber volume with increasing depth. Such findings illustrate how chamber placement and other features in the model do not necessarily require additional mechanisms, and that they may instead be the result of environmental limitations alone.

3.2 - Adding Site Selection and Colony Odour

So far, the placement of nests has been chosen randomly within the artificial world. However, the location of real ant nests is usually selected by the queen in the light of logs or stones or other environmental criteria. Once a site is chosen, ants of the developing colony display an awareness of where their nest and its entrance are, and do not just wander off and begin a nest somewhere else. This awareness may be due to changes in the chemical and physical properties of the soil after being modified by the ants and deposited at the surface (Wang et al. 1995). To loosely mimic such queen site selection and colony odour build up in the model, a single deposit of shaft pheromone of finite volume was placed at the centre of the world on the ground during initialisation. In contrast with regular shaft pheromone, this deposit did not decay with time, although it diffused outwards as normal. In this way, this pheromone deposit (through its effect on shaft excavation) increased the likelihood of a nest being started at that location as well as (through its effect on movement) serving as a permanent beacon that encouraged ants who have left the nest to deposit material to return.

The model simulation was run for 150 time steps using the altered parameters that were chosen for the CO₂ exploration discussed in the previous section. This time, such values meant that it was highly unlikely that a nest would be started without the presence of any pheromone, but that one would appear at the location of the special pheromone deposit almost immediately.

On one run the resulting excavation reached a depth of eighty units below ground and a height of six units above ground. The deepest chamber was at a depth of sixty-six units. Figure 9-4 illustrates this result.

Figure 9-4 An illustration of the nest excavation after 150 time steps, viewed in three dimensions.

The addition has allowed the population to focus their attention at one specific, pre-selected site, and is therefore comparable to real-world nest excavation in this respect.

3.3 - Surface Deposits

The realistic inclusion of both digging and depositing behaviours may provide some insight into how subterranean nests could be excavated, and also into how discarded material might be dealt with above ground. Observations have shown that discarded material often forms a characteristic species-specific crater or mound on the surface, although some species are known to scatter material in streaks or splashes (Wheeler and Wheeler 1986). Although there is not room in the present study to fully explore this substantial topic, there are certainly a few initial results that can be reported here. For instance, a combination of simple
probabilistic rules can lead to the construction of mounds at the entrances to nests. Figure 9-5 illustrates one such mound, which reached a height of seventeen units.

![Figure 9-5](image)

**Figure 9-5** A mound created from material discarded on the surface, viewed (a) from the side and (b) from above.

The shapes of these mounds may well be dependent on the probability of an ant depositing its block once above ground. Research has shown that for some types of ants, this value increases with an increase in walking distance since surfacing from the nest (Théralaz et al. 2003). It is also possible that minor alterations could easily lead to the formation of craters if, for instance, ants were less likely to deposit material within a certain distance of the nest entrance. This could be achieved either with knowledge of the entrance's location or by a pheromone, which decreased the likelihood of deposition, diffusing out through the entrance from within. The model is able, therefore, to mirror other real-world characteristics of ant nests, lending further support to the plausibility of its mechanisms.

### 3.4 - Termination Conditions

Stigmergy fails to explain how construction ends (Stuart 1967). Consequently, for the current model, there is no termination condition in which the nests stop being added to. Only one shaft is required per nest, whereas chambers are numerous within each nest. To reflect this, shafts are started with a very low probability and chambers are started with a much higher probability. The upshot is that, without a termination condition, although it is very unlikely that once all shaft pheromone has run out in a nest the shaft will then be extended downwards by another random start, chambers will be started and extended for as long as the run is allowed to continue (see Buhl et al. 2005). In real-world nests, however, continued growth tends to take the form of additional shaft branches, each of which has a modest number of chambers, rather than an indefinite increase in chambers to an existing shaft (see Figure 9-1).

To demonstrate this current limitation, a single run was allowed to proceed for 1000 time steps. The results can be seen in Figure 9-6 and Figure 9-7.

![Figure 9-6](image)

**Figure 9-6** An illustration of the nest excavation after 1000 time steps, viewed from side-on.

![Figure 9-7](image)

**Figure 9-7** The same nest excavation as that in Fig. 8-6, viewed in three dimensions.
It would appear that the virtual nests were started on about twelve separate occasions, although their close proximity to each other makes this hard to determine. In all, the nests had a maximum depth of seventy-two units and height of twenty-three units, and featured a few more shafts but many more chambers. The lack of a termination condition, or at least a mechanism for determining whether more excavation is required or not, will be discussed further in the next section.

4 - Discussion

4.1 - Objectives

This chapter has set out to produce a better understanding of how ants might use stigmergic rules and probabilistic behaviours to excavate their subterranean nests. The results demonstrate that the combination of carbon dioxide and pheromone gradients might provide relevant cues when attempting to model ant movement. These ideas, based on biological research, allow virtual ants the ability to excavate in a generally vertical direction, while enabling them to locate both sites at which to excavate and sites to deposit material.

These gradients successfully interact with the two abilities bestowed upon each ant: to pick up and to deposit. The current project is the first to include both behaviours, and these actions can only be realised if the ants have access to information allowing them to determine when and where each is appropriate. Although there is not yet sufficient real-world understanding of how such results come about, the current work provides an insight into possible methods of achieving these goals. The obstacle to be overcome is for ants to realise when they are beginning/extending shafts rather than chambers. Even incorporating a hypothetical directional inertia, whereby movement plays a reinforcing role over digging behaviours, seemed unable to sufficiently explain the way that real complex shaft and chamber structures interrelate. The addition of a second pheromone was therefore deemed necessary, and provided the artificial colony with the ability to place the different structural units in coherent and realistic formations. As such, we might conclude that real-world ants use at least two sources of information when considering in which direction to dig, and that separate pheromones could potentially provide them with this.

The existence of fewer chambers at increased depth, observed in nature, also occurred in our simulation results without the need to posit further behavioural mechanisms, supporting a new hypothesis that this characteristic may in the real world be due to simple stigmergic effects inherent in the interactions between ants and their environment.

The special pheromone deposit, loosely based on the real-world site-selection by the queen and ant awareness of the location of the nest entrance, succeeded in providing the virtual ants with a way of finding the nest again after depositing material and hence continuing with one nest instead of shifting their attention to the creation of further nests. As such, the addition produced realistic outcomes although the mechanism is unlikely to be completely accurate.

Finally, examination of some specific aspects provided a greater understanding of how well the model performed. For instance, the production of craters and mounds surrounding nest entrances, observed with real ants, was simply a by-product of the ants leaving the nests and dropping material with a certain probability. Once again, it may be that no complicated explanation is necessary for how this nest characteristic comes about. In addition, simulations of long-term excavation highlighted one of the downsides of the model presented here, namely that no termination mechanism was included. Such a feature is still not yet understood in nature, and will be discussed further in the next section.

4.2 - Further Work

Each simulation's success was primarily based upon subjective measures. This, for the most part, comprised a visual judgment of how realistic the nest excavations appeared to be in comparison with real-world ant nests. Although more objective measurements were used when investigating chamber placement, the general success of simulation runs was based upon some descriptive measures, such as the maximum depth and height reached, but mostly subjective three-dimensional observation of the resulting nests. This lack of more objective measures was the focus of research by Paulin (2004); such measures would remove any experimenter bias from the current work. However, a great deal more needs to be learned about why real ant nests take the form that they do (in contrast with termite mound construction, the functions of the structure of which are well understood e.g. Turner 2001) before we can begin to reach a set of useful objective measures.

If we could judge nests based upon more objective criteria, we would be able to optimise the parameters of a particular model much more quickly and efficiently using computerised search algorithms or similar, rather than the time-consuming by hand exploration and variation relying
upon intuition as to the fitnesses being aimed for (although neither method would guarantee the optimal results).

We also have to consider how realistic the model parameters actually are. If realism were the final goal of these models, then the parameters used would attempt to best reflect the ants and their environment as they are found in nature. Towards this end, we were influenced when choosing values. The carbon dioxide concentrations, for instance, were taken directly from biological studies (although the linear gradient used was a simplification of the actual relationship with depth). One of the difficulties is the sheer size of real-world populations and their nests. However, with improvements in computational power, it is likely that even these factors relating to scale could be incorporated.

A number of questions have arisen from the current research, in particular relating to how the ants decide when and in what direction they should dig in order to contribute to the nest as a whole when they have no knowledge of the current, or final, overall structure. One possibility is the use of digging specialists (Chen 1937a; Chen 1937b) and experience (Evesham 1992, Mikheev 2002), and this could be explored in further models, perhaps also dealing with the lack of commencement and termination conditions referred to above. On this last point, the current modelling assumption of constant probabilities for beginning structures is almost certainly a poor model of what happens in the real world, and the addition of a mechanism that the ants have some way of estimating the population size of the nest (perhaps by calculating the frequency of local interactions) may represent one plausible solution, with an incorporation of worker exhaustion providing another possibility (Buhl et al. 2005).

### 4.3 - Conclusions

In this research, we have begun to explore and understand how stigmergic processes might enable ants to excavate their subterranean nests. By giving our artificial ants a realistic repertoire of behaviours, and placing them in an environment that features sufficient cues, we were able to model, in three dimensions, one possible set of mechanisms for the entire process of nest excavation. While a few of the characteristics of the model have little basis in biological observation and as such are hypotheses with insufficient empirical grounding, the results produced and the questions raised are testaments to the success of the approach taken. Even extending beyond ants, this use of relatively complex stigmergic simulation has allowed us to model plausible solutions, and so test hypotheses relating to real-life behaviour, which represents a success of itself. In this way, the current research takes steps towards an increased understanding of possible processes at work as a colony creates the intricate world that is their home.

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