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Emergence in Complex Systems

Micro-study

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Decentralizing Navigation

Abstract

This project replaces the unrealistic hard-coded global coordinate tracking in ant foraging simulations with a decentralized olfactory mechanism. We do this by introducing a third pheromone called *Colony Pheromone*. We implement a diffusive pheromone gradient and demonstrate how precise homing behavior emerges solely from local agent-environment interactions, removing the need for internal cognitive maps or global positioning.

Problem

The global foraging simulations as currently defined hard-code the return journey home for the ants. That is, there is no actual mechanism implemented or explored for how ants find their way back to their nest after finding a food source. We want to explore a potential mechanism for such a return.

Background

Homing is defined the ability of an animal to return to its nest after traveling away from it. Foraging animals have been shown to display various different homing mechanisms as they are necessitated to wander away from their nests to find food sources. For ants, methods of homing are mainly olfactory.

Foragers establish pheromone trails on their way back to the nest after finding a food source to incentivize other ants from the nest to exploit the food source. These ants reinforce this pheromone trail on their return journeys, incentivizing more ants to exploit the food source. When the food source is exhausted, foragers deposit negative pheromones to signal

to the ants to not take that pheromone trail. Although ants that follow a pheromone trail to a food source can follow the same pheromone trail back to the nest, the first ant that finds the food source does not have access to that trail. Instead, in some ant species, the foraging ant leaves behind a separate pheromone as it explores which it can follow back to its point of origin, the nest.

Furthermore, some ant colonies deposit a very specific blend of chemicals around their nests in a process called 'Home Range Marking'. This serves the purpose of both warning other ants and intruders that they are in the territory of that colony, which is generally defended, and aids colony members in finding their way back once they are in the vicinity of the colony.

Even if there are no colony specific pheromones in the area, ants may learn the specific olfactory profile of the area around their nest. They can then use various olfactory landmarks in the area to help them navigate.

Finally, some species of ants have been shown to rely on visual cues. These ants perform walks around the nest before becoming foragers. During these walks, they look in the direction of the nest and in different compass directions. Then, during foraging walks, they can match what they are seeing with their takeaways from these learning walks to align themselves towards the nest.

Although the most prevalent method seems to be pheromone trailing, it comes with steep costs. If the pheromone trail the ants are following is severely distracted, groups of ants have been shown to form an orderly circle and follow each other indefinitely. In these cases, they generally neither make their way back to the nest nor go back to foraging.

Method

We decided to replace the hardcoded vector for returning home with a *Colony Pheromone* gradient. To do so, we introduced a third type of pheromone called the *Colony Pheromone*. We wanted the pheromone to be secreted at a gradient so that the ants are secreting less pheromone the further they are from the nest. This was meant to ensure that the concentration of the *Colony Pheromone* would get higher as the ants approached the nest, thus ensuring that following the path of the increasing pheromone would lead the ants back home.

Specifically, ants were given a stock of *50,000* pheromone units while at the nest. This value decays by *10* each step an ant takes to create the aforementioned decaying gradient. After an ant finds food, it looks for neighbouring cells with a higher concentration of the colony pheromone. It continues to follow this increasing gradient until it reaches the nest. A percentage of the pheromone evaporates each time step to prevent overloading the environment with the pheromone and to maintain relative concentrations, which are necessary for the pheromone to be effective.

We also modified the simulation so all ants acted simultaneously instead of the old asynchronous structure as this made the simulation more consistent with the real-world and made analysing what was happening at each time step easier.

The following overview summarises the main functions involved and how the updated behaviour is distributed across classes.

- Ant behaviour pipeline

```
Ant.moves()  
  If carrying food → returnHome()  
  Else → exploration logic:
```

```
Sniff()
Random escape move
Deposit Colony Pheromone
Deposit Negative Pheromone
Update taboo list (History)
Switch to BackHome mode if food found
```

- Returning to the nest

```
returnHome()
  If current position = nest:
    Reset PPStock and CPStock
    Clear taboo list
  Determine next cell via SniffForHome()
  If no candidate or random escape trigger:
    Move randomly
  Deposit Positive Pheromone (food trail)
  Decrease PPStock proportionally to nest distance
  Update taboo list
```

```
SniffForHome()
  Retrieve neighbourhood cells
  Exclude current cell
  Exclude taboo list cells
  Select neighbour with highest Colony Pheromone
  Return None if no valid candidate exists
```

- Pheromone dynamics

```
evaporate()
  Exponential decay of NP
  Exponential decay of PP
  Exponential decay of CP
  If any pheromone < threshold:
    Snap to zero
  Clean cell if all pheromones = 0
```

```
cpheromone()
  Modify Colony Pheromone concentration
  Add cell to ActiveCells for evaporation
  Update rendering (pink/red intensity)
```

Results

Across all simulation runs we performed, the introduction of the diffusive *Colony Pheromone* produced a rich variety of emergent behaviors that depended strongly on the chosen parameter configurations.

A first set of results concerns the behaviour of the pheromone field itself. When the system relied on linear evaporation, *Colony Pheromone* levels near the nest grew indefinitely, as returning ants deposited pheromone faster than it could dissipate. This produced unstable concentration profiles that did not reflect biologically plausible conditions.

Switching to exponential evaporation stabilised the system: pheromone quantities decreased proportionally to their magnitude, preventing unbounded accumulation and creating a self-balancing dynamic. However, exponential decay also introduced long-lasting residual traces. Extremely small pheromone values never reached exactly zero and persisted as faint tails on the map, cluttering the environment and consuming unnecessary computational resources.

To address both issues simultaneously, we introduced a cutoff threshold below which pheromone values are snapped to zero. This preserved the stability of high-intensity regions while eliminating negligible residues, resulting in a clearer and more efficient pheromone field.

```

1 if self.cp() > 0:
2     # Exponential decay:
3     evap_rate = self.cp() * (Gbl['ColonyEvaporation'] / 100.0)
4     self.cp(-evap_rate)
5     if self.cp() < Threshold: self.cp(-self.cp()) # Snap to 0

```

The most significant behavioural results involve the emergence of circular motion patterns. In the initial stages of development, ants frequently became stuck in small local loops: oscillating between neighbouring high-pheromone cells or remaining confined inside minor local maxima. These micro-loops can be interpreted as early manifestations of the same mechanism that later gives rise to full circular milling.

To reduce these preliminary forms of oscillatory trapping, we introduced two mechanisms:

- a “Taboo List”, where ants remember their last six positions and avoid revisiting them;
- a small probability of random escape movement.

These modifications substantially reduced the formation of small oscillatory loops by interrupting self-reinforcing motion patterns before they could stabilise.

```

1 self.History = []
2 self.HistorySize = 6
3 ...
4 if NewPos in self.History: continue
5 ...
6 self.History.append(self.location)
7 if len(self.History) > self.HistorySize:
8     self.History.pop(0)

```

Despite these improvements, in some parameter configurations the system still produced persistent circular formations: once a group of ants entered rotation, the pattern tended to self-sustain for the remainder of the simulation. Crucially, this behaviour is not an artifact of the model: circular milling, or “ant mills”, is a well-documented biological phenomenon, occurring when ants become trapped in self-reinforcing pheromone loops. Its appearance in our simulation therefore reflects a realistic emergent behaviour.

The biological interpretation of this phenomenon will be explored in detail in the following section.

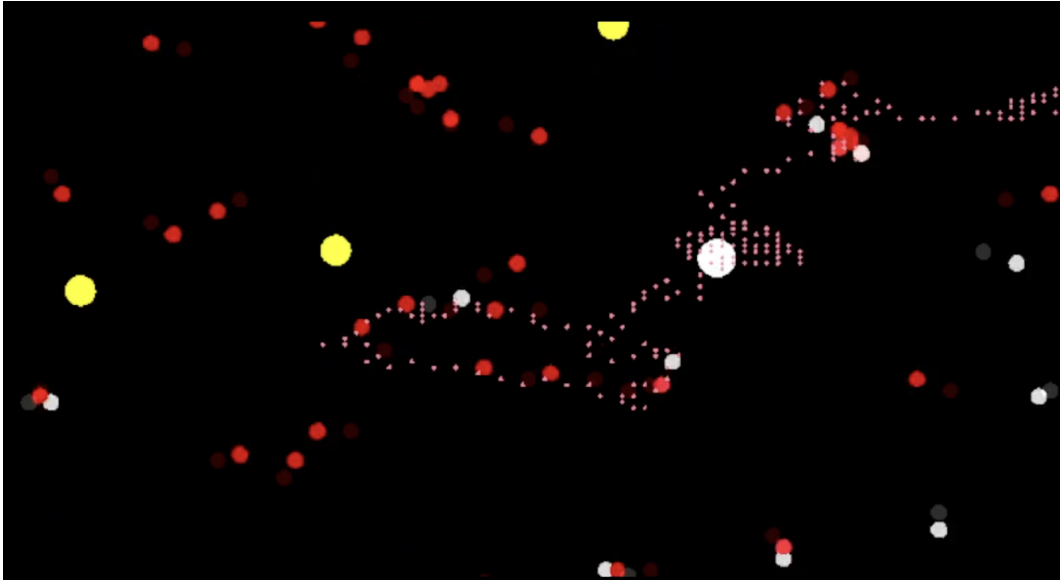


Figure 1: Circular milling behaviour observed in the simulation.

Rather than attempting to eliminate circular milling entirely, which would require imposing additional artificial constraints and would reduce biological plausibility, we focused on reducing its frequency. By tuning key hyperparameters, specifically the pheromone evaporation rate and the amount of *Colony Pheromone* deposited, we were able to make milling rare across the vast majority of runs. This reduction is sufficient to consider the system stable while still allowing it to reproduce characteristic emergent behaviours found in real ant societies.

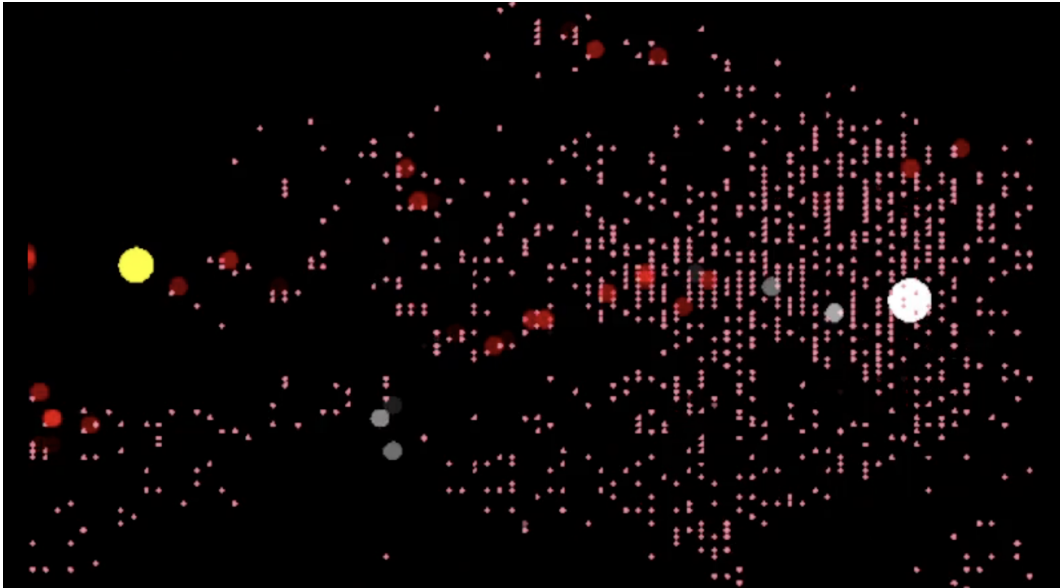


Figure 2: Example of a successful simulation without circular milling.

Discussion

The simulation results confirm that ants can find their nest without using a "hard-coded" GPS or coordinate subtraction. In the original model, ants used global knowledge—they "magically" knew exactly where the nest was (X, Y coordinates) relative to themselves. In

our modified model, we replaced this with local knowledge. By simply following the trail intensity, the ants navigate successfully. The "pink fog" of *Colony Pheromone* essentially functions as an externalized cognitive map; by depositing pheromones during exploration, the colony constructs a physical memory of its history. This demonstrates that the "intelligence" of the system resides not in the individual agent but in the ants as a collective.

The "Ant Mill" Phenomenon: As noted in the results, early versions of our simulation failed because ants got stuck in infinite circles (circular mills) theoretically, this occurs because the local rule ("follow max pheromone") creates a positive feedback loop: the more a circular path is traversed, the stronger it becomes, trapping agents in a local maximum. This confirms that pure gradient ascent without error correction is inherently fragile in complex geometries.

Our Solution: Memory and Randomness To break these loops, we implemented two simple changes in the code, often referred to as adaptive stochasticity (or "useful randomness").

1. We gave each ant a short-term memory of its last 6 steps. If a move would take it back to a spot it just visited, it is forbidden. This prevents the ant from vibrating back and forth between two cells.
2. *The Random Noise Factor:* For larger circles, memory isn't enough. We added a 5 percent chance for the ant to ignore the pheromone entirely and move randomly. This "noise" is crucial because it breaks the symmetry of the circle, kicking the ant out of the loop so it can find the real path home.

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Main Limitation: Because the pheromone evaporates or decays over time, there is a maximum distance from the nest where the signal works. If an ant goes beyond this "horizon," the trail home has already vanished by the time it turns around. Navigation is only possible within the radius where the pheromone signal exceeds the pheromone evaporation rate, limiting the effective foraging range compared to the infinite-range vector model. This suggests that in real decentralized systems, exploration must happen slowly and incrementally, expanding the territory only as fast as the pheromone network can support it.

Further Directions

Although functional, the paths created by the ants in our simulation were suboptimal as they were a direct result of the pathways they took during exploration. We know that in the physical world, ants trails are more efficient. A potential future direction for the work would be adding multiple other homing mechanisms to work in tandem with the trail pheromones, as there is no indication that ants only use one mechanism at a time and in fact some evidence that they do combine methods.

Another potential direction could be exploring having various ant colonies within the simulation environment. Since ant trails may intersect and interact with each other and this would introduce competition for food sources, an interesting direction would be exploring these interactions and how trails may evolve differently to accommodate the presence of other colonies.

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