知 能 と 複 雑 系 108－5
（1997. 5. 26）

巨視的な群挙動の創発の条件解析に向けて
－蟻コロニーの採餌行動を例題として－

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Toward Analysis Method for Emergent Group Behaviors at Macro-Level
– An Example from Ant Colony's Foraging

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May 26, 1997

Abstract

We propose a method of automatically generating qualitative equations, i.e., monotonic and differential relations among the variables, to model and analyze macro-behaviors of foraging in ant colony. Foraging is a well-coordinated group behavior of ant colony, which is achieved by the cooperation of individual ants. We executed numerical simulations for the foraging behaviors to see what happens in the colony, and implemented a reasoner which can predict the most basic characteristic of foraging behaviors, i.e., continuous growth of the number of ants gathering to a bait-site.

1 Introduction

In this paper, we present a method of automatically generating qualitative equations for foraging behaviors of ant colony with qualitative reasoning, which is one of the symbolic computation methods to model and simulate dynamical systems.

Foraging is a well-coordinated group behavior of ant colony with communication methods by chemical pheromone, which is achieved by the cooperation of individual ant which obeys a simple behavior rule at micro level. On the other hand, the group behavior at macro level can be very complex.

Usually it is difficult to analyze what is happening at macro level in the colony. Our approach is to generate qualitative equations, i.e., monotonic and differential relations among the variables representing the colony at macro level, in order to explain the behaviors of the colony and provide help for human users.

For the purpose, we prepare fragments of knowledge about the foraging behavior, called *macro-behavior rule,* consisting of condition part under which a fragment of knowledge is valid and conclusion part which represents the conclusion drawn from the knowledge. The reasoner applies the macro-behavior rules to the given state, and it concludes what is happening in the colony, while generating qualitative equations.

Because foraging is an essentially space-oriented behavior, i.e., ants and pheromone are distributed in a two-dimensional space,

the method is required to represent and reason about spatial characteristics of colony's behavior. We prepare symbolic representation called *qualitative region* for the purpose.
First, we report the results of numerical simulations of foraging behaviors in an ant colony model under several conditions, in order to observe the foraging behaviors at micro-level.
In the rest of paper, we propose a method of generating qualitative equations. We implemented a reasoner which can predict the most basic characteristic of foraging behavior, i.e., continuous growth of the number of ants gathering to a bait-site.

2 Foraging Behavior of Ant Colony

Foraging behavior is an organized behavior of ant colony with local communication methods by chemical pheromone. Although the behavior of individual ant is quite simple, the colony shows very complex behaviors.
It has macro-goals at the colony level, such as maximizing the bait transport ratio and minimizing the risk caused by environmental disturbance, i.e., climate, food competition, and so on [3].
The macro-behavior must be achieved by the cooperative behaviors of individual ant. The individual ant have a local communication method with chemical pheromone, but the colony itself has no global communication methods. The colony must therefore achieve its macro-goals by coordinating or tuning the individual micro-ant behavior.
In this paper, the model of each ant behavior is assumed to be as follows (also shown in Figure 1).[1]

[Foraging behavior of individual ant]

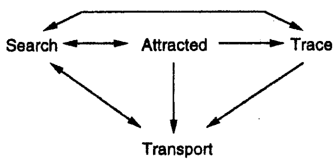
1. At any time, an ant is in one of these modes: *search, attracted, trace,* or *transport.*
2. *Search* is the default mode. In this mode, an ant moves randomly in the space.
3. When an ant in any mode finds a bait-site, it turns into *transport* mode, in which it carries a bit of bait back to the colony's nest. Bait can exist at several bait-sites. An ant in transport mode secretes recruitment pheromone on its transportation path, which becomes the pheromone 'trail.' An ant in transport mode turns into search mode when it reaches the nest.
4. The trail evaporates and diffuses, which produces a pheromone atmosphere (We call the pheromone atmosphere just 'pheromone' in this paper).
5. When an ant in search mode comes across a pheromone atmosphere, it turns into *attracted* mode, in which it is induced by the pheromone and moves toward a position of higher pheromone density. If the pheromone disappears before the ant in attracted mode find a trail, it turns back to search mode.
6. When an ant in search or attracted mode finds a trail, it turns into *trace* mode, in which it traces the trail in the opposite direction of the nest. If the ant in trace mode cannot find a bait at the end of trail, it turns into search mode.

An ant in trace or transport mode must have the ability to recognize the direction of the nest. There are two assumptions about the ability. The first one is that ants can recognize the direction by the height and the angle of the sun. The second one is that 'nest pheromone' is being secreted at the nest and each ant can recognize the direction of the nest by the gradient of the pheromone density.
This simple algorithm of individual ant realizes the foraging behavior of the colony, i.e.,

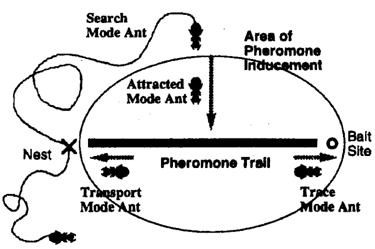
[1] The model is not entirely faithful to real ant behavior. It represents common aspects of many kinds of ant colonies.

1. to find the bait-site(s),
2. to mobilize ants in the colony in order to carry bait on a large scale, therefore,
3. to maximize the bait transport ratio.

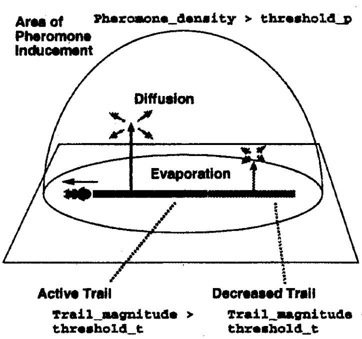
Notice that this simple algorithm (and the colony's strategy) can be easily influenced by an environmental disturbance. When more than one bait-site exists and all the ants in the colony gather to a bait-site simultaneously, enemy animals can easily attack the colony. The colony might also miss other bait-sites which have more bait than the bait-site currently under attack.



(a) Mode transition of ant.



(b) Behavior of each ant.



(c) Evaporation and diffusion of pheromone.

Figure 1. The foraging behavior system.

3 Numerical Simulations

We have carried out numerical simulations of the foraging behavior with several sets of parameters [7] [8]. Part of the results of the simulations is shown in Figure 2.

In these simulations, a nest exists in the center of the environment, and there are eight bait-sites equidistant from the nest. The only difference between the two is the number of ants in the colony.

Other important parameters are as follows:

Expansion of simulated space
$0 \leq x < 100\Delta x,\ 0 \leq y < 100\Delta y,\ 0 \leq z < 3\Delta z$
Length of a grid and a step
$\Delta x = \Delta y = \Delta z = O(0.01 \sim 0.1m)$,
$\Delta t = O(1 \sim 10sec)$
Moving speed of ants in all mode
$2 \sim 3\ (\Delta x/\Delta t)$
Evaporation and diffusion factors
$\gamma_{eva} = 0.24\ \Delta t,\ \ \gamma_{dif} = 0.42\ (\Delta x^2/\Delta t)$
Minimum sensitive trail strength 0.0001
Minimum sensitive pheromone density 0.001
Pheromone secreted by an ant for a step 0.001

In Figure 2(a), there are 60 ants searching for 8 bait-sites. Some ants actually find a bait-site and generate a pheromone trail between the bait-site and the nest. Since the trail evaporates more quickly than enough number of other ants gather to the trail, continuous growth of the trail and continuous large-scale transport are not achieved. In Figure 2(b), there are 600 ants. They are able to gather to the trail, and large-scale transport is achieved. The results indicate that there must be a large enough number of ants in the colony to overcome the time-delay between the gathering speed of the ants and the evaporation/diffusion speed of the pheromone.

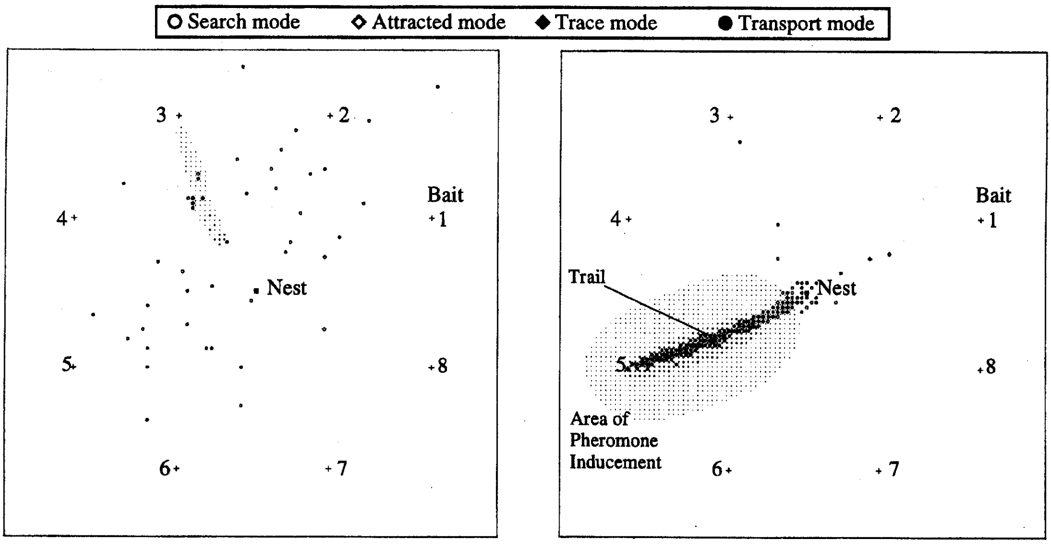


Figure 2.1. The distribution of ants after 1000 simulation steps.

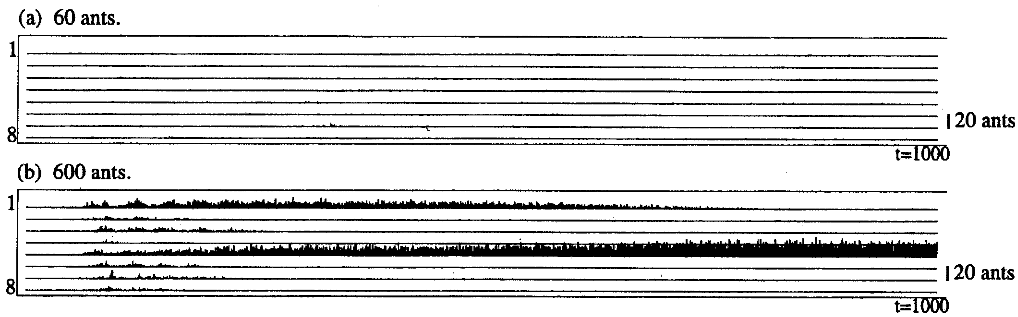


Figure 2.2. The number of ants which reached bait sites.

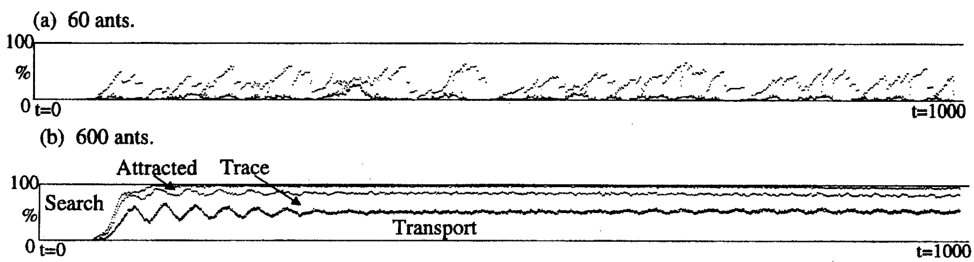


Figure 2.3. The percentage of ants in each mode.

Figure 2. Numerical simulation of the foraging behavior for 60 (a) and 600 (b) ants.

In Figure 2(b), almost all of the ants gather to the bait-site number 5. The colony basically "forgets" the other bait-sites. Actually the same phenomenon that all the ants gather to only one bait-site is observed under almost all parameters whenever large-scale transport is realized. The reason is that there is a positive feedback in the differential relations of the system parameters, i.e., the number of ants gathering to a bait-site, the amount of secreted pheromone by the ants, and the amount of evaporated pheromone atmosphere which attracts the ants.

Although human experts could find this kind of proportional relations in the system, it is fairly difficult for beginners to do so, because they lack enough mathematical knowledge about the system, or they cannot reason about the behavior with this kind of knowledge.

In the following sections, we propose a method of generating qualitative equations, which can be used to model and reason about such phenomena.

4 Qualitative Region

Because foraging is an essentially space-oriented behavior, i.e., ants and pheromone are distributed in a two-dimensional space, the method is required to represent and reason about spatial characteristics of colony's behavior.

For the purpose, we use the notation of *qualitative region.* A qualitative region represents a spatial extent describing an attribute of the colony and its changes, e.g., how the pheromone trail or atmosphere spreads, or how ants in a certain mode are distributed in the space.

Mathematically, when a function $f(x, y)$ and a meaningful value l (a landmark) are given, the notation (predicate) `region(r, f, l)` means that r is the boundary which is determined by $f(x, y) = l$. The notation `region(r, f, l, +)` means that r is an open region $f(x, y) > l$ (Figure 3). If more than one such region exists, they denotes a set of regions.

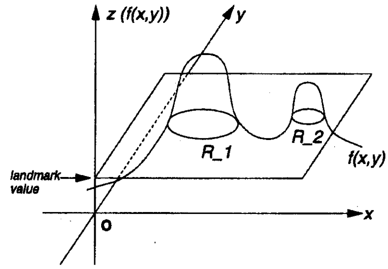


Figure 3. Qualitative regions.

Since our aim is not to represent such regions precisely (it can be done within numerical simulations), we extract some characteristics of the regions.

Although one method of representing the characteristics is to describe the boundary of a region qualitatively [4], in this paper, we extract the area of a region, the amount of entity included in a region, the topological relations among regions, etc., as follows.

- Class of region: A class has common descriptions to instance regions belonging to the class, e.g., the manner of the change of regions (equation type), i.e., *diffusion, evaporation, constant.*

- Characteristic properties (qualitative variables) of a region, i.e.,

  $area(region)$
  $total\_amount(region)$
  $average\_amount(region)$

  are prepared and can be used in the reasoning process.

- Topological relations between two regions, i.e.,

  ```
  identical(ra, rb)  isolated(ra, rb)
  intersect(ra, rb)  include(ra, rb)
  ```

  can be asserted as predicates in the reasoning process.

5 Generating Qualitative Equations

5.1 Macro-Behavior Rules about Ants

Our approach is to prepare fragments of knowledge about the colony's behavior at macro level, in the form of *macro-behavior rule,* which is valid in a situation. It consists of the conditions by which the rule is activated and the conclusions which we can draw for the situation. The reasoner applies them to a given situation in turn in order to construct a model of the behavior, and consequently generates qualitative equations to the situation, i.e., qualitative relations among variables representing the colony at macro-level.
For instance, in a situation where ants in search mode come across a pheromone atmosphere and they will turn into attracted mode, the transition frequency from search to attracted mode is qualitatively (monotonically) proportional to the population of the ants in search mode, and also to the area of the pheromone atmosphere, described as follows.[2]

```
MO+(trans_freq(search, attracted),
    population(search)).
MO+(trans_freq(search, attracted),
    area(phero)).
```

The predicate `MO+(a,b)` is a qualitative relation which means that a is monotonically proportional to b, i.e., $\partial a/\partial b$ is positive, and $a = 0$ when $b = 0$. Another qualitative relation `I+(a, b)`, which appears later, means that a is qualitatively influenced by b, i.e., $[da/dt] = ... + [b] ...$, where $[x]$ is the sign of x. These qualitative relations are primitives to constitute qualitative equations of the colony's behavior at macro level.
The whole definition of the rule for transition from search to attracted is written as follows.

[2]Because we represent the distribution of ants in a mode as a qualitative region, `population(mode)` is equivalent to `total_amount(mode)`. The former is an alias of the latter.

```
transit(search, attracted) {
 %% condition part
  involved_regions :
     region(Search, search_region).
     region(Phero,  phero_region).
  region_topology :
     have_intersect(Search, Phero).
 %% conclusion part
  new_regions :
     region(Attracted, attracted_region).
  new_region_topology :
     include(Phero, Attracted).
  new_quantity_relations :
     MO+(trans_freq(Search, Attracted),
         population(Search)).
     MO+(trans_freq(Search, Attracted),
         area(Phero)).
     I-(population(Search),
        trans_freq(Search, Attracted)).
     I+(population(Attracted),
        trans_freq(Search, Attracted)).
}
```

The predicate `region(X, class_region)` means that `X` is an instance in the class `class_region`.
The predicate `have_intersect(X, Y)` means that two regions `X` and `Y` have some intersection. For the predicate, it is insufficient just to verify whether `intersect(X, Y)` holds or not, because there is a possibility that two regions have some intersection via other regions, e.g., `have_intersect(X, Y)` $\vdash$ `intersect(X, Z)` $\wedge$ `include(Y, Z)`. The reasoner maintains this lattice structure of region inclusion relations and handles the predicates properly.
An argument of a quantity beginning with uppercase is a variable for region, which the reasoner unifies to an instance region in the database for the current state, like regular prolog systems.

5.2 Macro-Behavior Rules about Physical Entities

All physical entities appearing in our problem (pheromone, trail) are also described as qualitative regions, e.g.,

```
region(phero, phero_region).
equation_type(phero_region, diffusion).
```

The latter predicate indicates that an instance region in the class **phero_region** changes with governed by a diffusion equation.
The macro-behavior rule for such a physical entity describes the manner of the change of the entity, e.g., the rule for a diffusing entity like pheromone is written as follows:

```
solve(diffusion) {
 %% condition part
  involved_regions :
     region(R, Class).
  conditions :
     equation_type(Class, diffusion).
 %% conclusion part
  new_quantity_relations :
     M0+(area(R), total_amount(R)).
     I-(total_amount(R),
        diffusion_rate(R)).
     constant(diffusion_rate(R)).
}
```

When generating qualitative equations, this kind of rule is used to check the equation type of a certain physical entity, and to reason about the change of concerning parameters.

5.3 Reasoning Process

A macro-behavior rule is a declaration "how the target system behaves in a certain situation." During the reasoning process, both types of the rules are treated uniquely.
The reasoner receives a set of macro-behavior rules and applies them in turn to a given initial state [5]. The detail of the reasoning process is as follows:

1. Set the initial state to the *current_state.*
2. Apply the macro-behavior rules to the *current_state,* and determine which rule becomes active.
3. If there is no rule which can be activated, stop.
4. Collect the qualitative relations in the activated rules.
5. Examine the possibility for each parameter to cross the landmark, and also examine the possibility that topological relations change (spatial version of limit analysis).
6. Collect the fragments of the next state in the activated rules, and set it to the *current_state.*
7. Go to 2.

This process resembles one from qualitative process theory [2] [1]. The difference is that 1) the macro-behavior rule, which corresponds to *individual view* and *process* in qualitative process theory, is uniquely represented as a macro-behavior rule, and 2) spatial extents, such as pheromone diffusion, can be represented and reasoned about with qualitative regions.
The example of the initial state is as follows:

```
initial_state_of_the_problem {
  assertions :
     region(nest, constant_region).
     region(bait, constant_region).
     isolated(nest, bait).
     region(search_1, search_region).
     include(search_1, nest).
}
```

Main part of qualitative equations, generated from the above initial state, is shown in Figure 4. A node is a quantity (variable or constant) representing an attribute of the colony, and an arc is a qualitative relation between two quantities. In the graph, there is a positive feedback concerning the number of ants gathering to bait, the amount of secreted trail, and the amount of evaporated pheromone atmosphere. This feedback causes the large-scale recruitment in transportation of bait [6], which was empirically observed in numerical simulations.

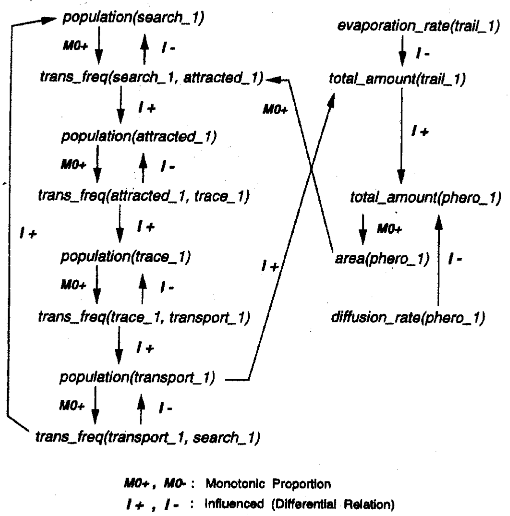


Figure 4. Generated qualitative equations.

6 Conclusion

A method of generating qualitative equations for macro-behavior of ant colony's foraging has been discussed.

Since the qualitative equations represent the underlying mathematical structure of ant colony's macro-behavior, the reasoner can find the macro properties, such as positive/negative feedbacks embedded in the system, which can be used in redefining individual ant's behavior.

Potential applications include explanation generation for novice users to understand the mathematical structure of the target system, and to provide help for experts to analyze the system.

References

[1] B. Falkenhainer and K. D. Forbus. Setting up large-scale qualitative models. In *Proc. of AAAI-88*, pages 301–306, 1988.

[2] K. D. Forbus. Qualitative process theory. *Artificial Intelligence*, 24:85–168, 1984.

[3] B. Hoelldobler and E.O. Wilson. *The Ants*. Belknap Press, 1990.

[4] K. Kurumatani. Reasoning with multivariant qualitative spaces. In *Proc. of Pacific Rim Int'l Conf. on Artificial Intelligence, PRICAI-90* (Nagoya), pages 390–395, 1990.

[5] K. Kurumatani. Generating causal networks for mobile multi-agent systems with qualitative regions. In *Proc. of IJCAI-95* (Montréal), pages 1750–1756, 1995.

[6] K. Kurumatani and M. Nakamura. Qualitative analysis of causal graphs with equilibrium type-transition. In *Proc. of IJCAI-97* (Nagoya), in printing, 1997.

[7] M. Nakamura and K. Kurumatani. A mathematical model for the foraging of an ant colony and pattern formation of pheromone trail. In *Fundamental Theories of Deterministic and Stochastic Models in Mathematical Biology*, pages 120–131. Institute of Statistical Mathematics, 1995.

[8] M. Nakamura and K. Kurumatani. Formation mechanism of pheromone pattern and control of foraging behavior in an ant colony model. In *Proc. of Fifth Int'l Conf. on Artificial Life, ALife V* (Nara), pages 48–56, 1996.